Bulletin
of
The Geological Society of America

VOLUME 62 July 1951 NUMBER 7

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Subscription $15.00 per year.

Publication Office: Mt. Royal & Guilford Aves., Baltimore 2, Md.

Communications for publication should be addressed to The Geological Society of America, Dr. H. R. Aldrich, Secretary, 419 West 117th Street, New York, N. Y.

NOTICE.—Four weeks notice of change of address is necessary. In accordance with the rules established by the Council, claims for non-receipt of the preceding number of the Bulletin must be sent to the Secretary of the Society within three months of the date of the receipt of this number in order to be filled gratis.

Entered as second-class matter at the Post-Office at Baltimore, Md., under the Act of Congress of July 16, 1894.

Accepted for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 8, 1918.

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VOL. 62, PP. 707-724, 1 FIG., 2 PLS. JULY 1951

BARITE CONCRETIONS FROM THE OCEAN FLOOR

By ROGER REVELLE AND K. O. EMERY

ABSTRACT

In 1938, a dredging from the sea floor off California recovered about 6 kilograms of tubular, sub-spherical, flat, and irregular shaped barite concretions embedded in marine mud. These are poorly sorted in weight and size. They range from 1 to 25 centimeters in length. The physical, chemical, and mineralogical characteristics of the nodules are described and compared with those of other barite concretions found on land or dredged from the sea floor. Barium sulphate is present in amounts up to 77 per cent, in the form of small radial aggregates often within the tests of Pliocene Foraminifera.

Various theories of the origin of barite concretions are discussed and tested in terms of those characteristics which seem to be of genetic importance. It is believed that the most probable mode of origin was the interaction of interstitial sulphate-rich sea water of the sediment with ascending magmatic waters containing dissolved barium and strontium. Various bits of evidence suggest that the two other reported occurrences of barite concretions on the sea floor had a similar origin.

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INTRODUCTION

During 1938, a program of geological investigation of the ocean floor off the California coast was carried on under the direction of Dr. F. P. Shepard, as a project of the Geological Society of America. In the course of this work, a series of dredgings was made from the

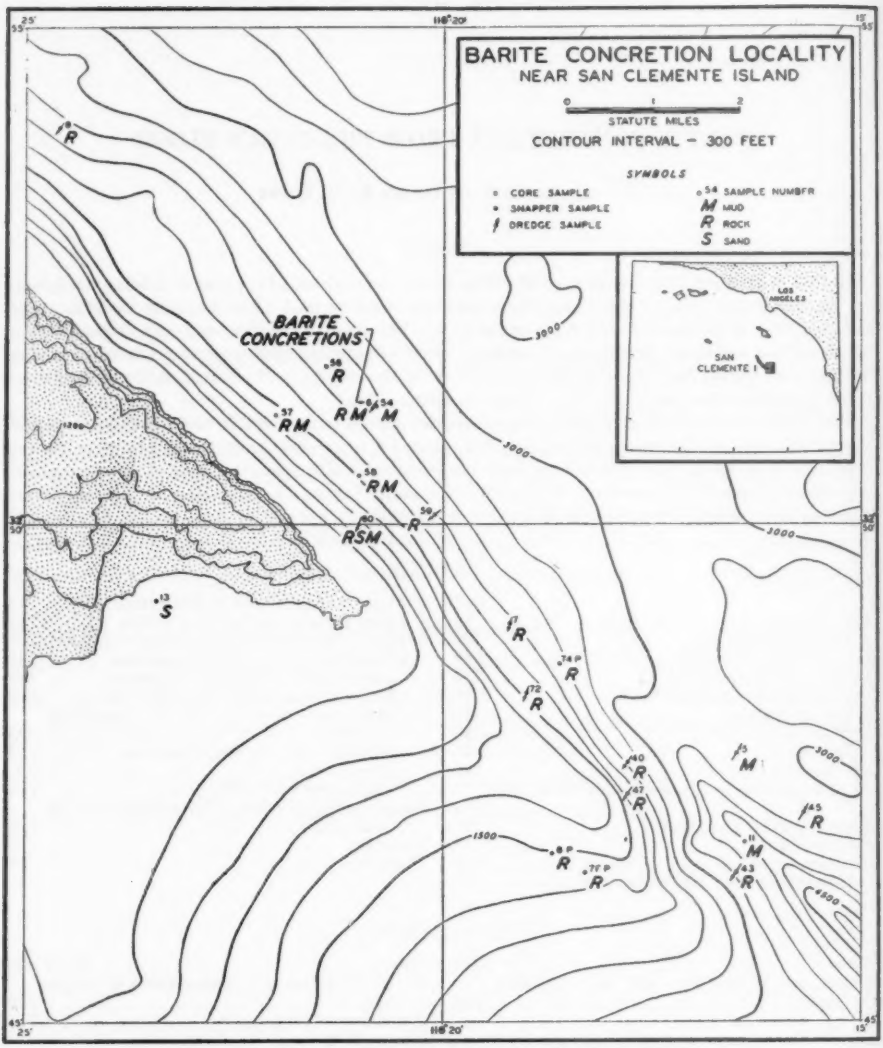


FIGURE 1.—BOTTOM TOPOGRAPHY OFF SAN CLEMENTE ISLAND
Showing position of Station 6 where a dredging recovered barite concretions. Note locations of adjacent samples in which the concretions were absent.

vessel E. W. SCRIPPS along the probable fault scarp which forms the north-east side of San Clemente Island (Fig. 1). One of these, made at a depth of 800 to 650 meters, recovered about 100 kilograms of green mud which contained 250 loosely mixed concretions. A few angular fragments of andesite were also present. The area of occurrence of the concretions is apparently very limited because none were found in later dredgings and cores from the same vicinity.

ACKNOWLEDGMENTS

The discovery of the concretions was made possible by a grant of the Geological Society of

America which permitted the taking of a large number of sea floor dredgings off California, one of which encountered the barite locality. Especial gratitude is expressed to Mr. M. L. Natland, who identified the Foraminifera within the concretions and the mud matrix. Appreciation is also due to Dr. F. P. Shepard and to Dr. R. S. Dietz, both of whom offered many helpful suggestions during the investigation. Assistance in the preparation of these materials was furnished by the personnel of Works Projects Administration, Official Projects 165-03-6999 and 465-03-3-403.

General Characteristics

The concretions range from less than 1 cm. to about 25 cm. long, and in weight from about 2 grams to nearly 1300 grams, with a median weight of 60 grams. They are poorly sorted; the weight distribution curve has maxima in the weight groups of 10–20, 80–160, and 640–1280 grams. The latter fraction, however, contains only one concretion. The total weight of all concretions is 6 kilograms.

The nodules were classified according to shape as: (1) tubular, elongate, or ellipsoidal, (2) equidimensional, or subspherical, (3) thin and flat, and (4) irregular or branching. Some of the concretions have warty or rough surfaces, occasionally with nipple-like protuberences. The remainder are relatively smooth (Pl. 1). In general, the smooth ones are softer and more friable than those with rough surfaces.

In contrast to the greenish-gray mud in which they occur, the concretions with rough surfaces are brownish-gray, while the smooth ones are similar in color to the mud. Many concretions of various types have a relatively hard and compact outer shell surrounding a softer core of more porous appearance (Pl. 2, fig. 1). The outer shell may consist of several layers, and is generally darker than the core.

Table 1.—Weights and Average Bulk Specific Gravity of Different Types of Concretions

Type of concretion	Number	Average weight grams	Range in weight grams	Per cent of total weight	Average bulk specific gravity	Range in specific gravity
Tubular warty	7	15	5–61	2.1	3.27	3.20–3.36
Rounded warty	4	96	25–244	7.6	2.73	2.62–2.78
Flat warty	59	12	5–63	13.4	2.72	2.52–2.93
Tubular smooth	27	49	10–180	25.9	2.70	2.20–3.18
Irregular warty	12	98	15–920	23.2	2.67	2.43–3.08
Rounded smooth	49	29	4–256	27.8	2.62	2.31–2.93
		—			—	
Median		60			2.69	
Enclosing mud					1.51	1.42–1.69
Moreno nodules	20				3.67	3.20–3.88

An approximate measure of the bulk specific gravity of many of the concretions was obtained after they had been washed free of the enclosing mud and dried. The weight was determined with a spring balance, and the volume by measuring the amount of water that they displaced. No relation between size and bulk specific gravity was observed (Table 1). With one exception, the rough-surfaced concretions have higher average bulk specific gravities and a smaller range in bulk specific gravity than the smooth ones. Table 1 also shows for comparison the bulk specific gravity of the mud in which the concretions were found and of a group of barite nodules from the Cretaceous Moreno shale, near Coalinga, (Anderson and Pack, 1915) kindly sent to us by Dr. Ralph Stewart, of the U. S. Geological Survey. The sea floor concretions are considerably denser than the surrounding mud, but much less

dense than the Moreno shale concretions. It will be shown later that this difference is due to a lack of pore space in the Cretaceous concretions.

A pipette mechanical analysis of the enclosing mud gave a median diameter of 4 microns and a sorting coefficient of 5.5. The sample contained 11 per cent sand, 36 per cent silt, 22 per cent clay, and 31 per cent colloid.

Petrographic Examination

Examined in thin-section, the concretions are found to consist in part of barite and in part of clay, detrital minerals, and organic remains. The barite occurs chiefly as small radial aggregates that range up to 0.2 mm. in diameter. These are commonly closely interlocking but the interference crosses of individual aggregates are easily observed by revolving the microscope stage under crossed nicols (Pl. 2, fig. 2). Barite is present in larger, more definite aggregates in the outer layer of a zoned concretion than in the core. Most of the aggregates include clay grains and some even contain a large detrital grain. Barite crystals are best developed inside the tests of Foraminifera. Because of the small size of the crystals, the indices of refraction could not be measured accurately, but were observed to lie between 1.63 and 1.65.

Beside barite and clay grains, the inorganic constitutents include plagioclase (chiefly labradorite), basalt-andesite fragments, glauconite, and minor amounts of augite, hornblende, biotite, collophane, and hematite. Siliceous sponge spicules, calcareous echinoid spines, and foraminiferal tests are also present. The general absence of quartz and the arkosic nature of the sand grains reflects the basic character of the rocks of San Clemente Island from which the detrital material may have been derived.

In the concretions of tubular, rounded, or irregular shape, fine-grained materials predominate, and minerals other than barite and clay never exceed 10 per cent. The flat concretions contain a much larger proportion of coarse grains, chiefly plagioclase, glauconite, and foraminiferal tests (Pl. 2, fig. 3).

Spectrographic Examination

A concretion of the round smooth type, the separated outer and inner portions of one of the tubular smooth group, and a sample of the enclosing mud were examined spectrographically by Dr. T. G. Kennard (Table 2).

Barium is present in relatively large quantities in the concretions but is found only as a trace in the mud. Likewise, strontium is more abundant in the concretions. All of the other major constituents except potassium appear to be present in approximately equal amounts in the concretions and the mud. Nickel and fluorine are more abundant in the mud, while lead and titanium are less abundant or absent.

A comparison of the spectrographic results with the very complete chemical analysis of a composite sample of green and blue muds published by Clarke (1924) shows certain qualitative differences in the content of minor elements. Boron, gallium, fluorine, and lithium were found only in our material, while vanadium, arsenic, molybdenum, and zinc, although listed by Clarke, were not detected in our samples.

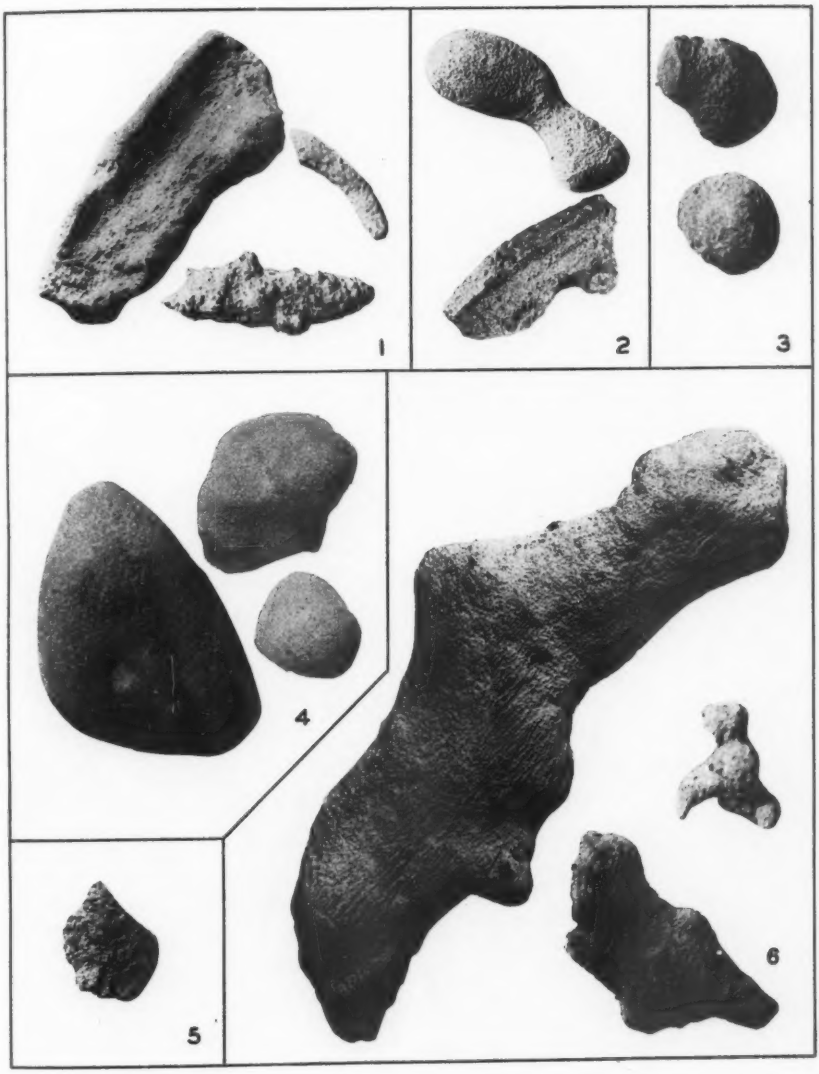
Chemical Analyses

Methods

The samples that were examined spectrographically were also chemically analyzed, principally by Mr. J. D. Laudermilk. Air-dried samples weighing approximately half a gram were used. After determination of ignition loss, the material was treated with boiling 10 N. hydrochloric acid and the acid-soluble and insoluble fractions were then analyzed separately. Barium was obtained by dissolving a portion of the acid-insoluble fraction with hot concentrated sulphuric acid, filtering and precipitating as the sulphate. Silica remaining in the precipitate was removed by evaporation with hydrofluoric acid.

Plate 1.—SHAPES AND SURFACE CHARACTERS OF CONCRETIONS

Showing the six groups described in the test: (1) tubular warty; (2) tubular smooth; (3) round warty (4) round smooth; (5) flat warty; and (6) irregular warty. Scratches on large one were produced by brushing. × 0.4



SHAPES AND SURFACE CHARACTERISTICS OF CONCRETIONS

FIGURE 1

FIGURE 2

FIGURE 3

SECTIONS OF CONCRETIONS

The remainder of the acid-insoluble fraction was fused with sodium carbonate. Analyses of silica, iron (as the sesquioxide), calcium, and magnesium in this fusion and in the acid-soluble fraction were carried out by standard methods (Hillibrand and Lundell, 1929). Sulphate was precipitated as $BaSO_4$ from the water soluble part of the sodium carbonate fusion. Strontium was not determined separately, but was probably precipitated in large part with the calcium. In a separate investigation, Mr. Howard T. Odum found that the ratio of strontium to calcium atoms in another one of the concretions was 0.070. If this ratio is correct for the concretions of Table 3, SrO would constitute 0.49, 0.47, and 0.93 per cent, respectively with CaO reduced in proportion.

Separate samples had to be taken for the determination of P_2O_5, Al_2O_3, and F because of interference between these substances. The P_2O_5 was determined in the usual manner by means of ammonium molybdate in nitric acid solution, after three evaporations to dryness to eliminate chlorine. In the Al_2O_3 determination, fluorine, which prevents complete precipitation of alumina by ammonia, was first removed by evaporation to fuming with sulphuric acid. Fluorine was determined by a quantitative spectrographic method. Sodium and potassium were determined directly on a separate portion, after a fusion with ammonium chloride and calcium carbonate, as uranyl zinc sodium acetate and potassium cobaltinitrate, respectively. Water was determined separately only on the mud, using a modified Penfield method. The percentage of CO_2 was estimated from the amount of acid-soluble calcium. Dissolved chloride was measured by titration of the solution obtained from repeated leaching of the samples with distilled water. In Table 3, it is assumed for simplicity that the chloride is present exclusively as NaCl.

TABLE 2.—SPECTROGRAPHIC EXAMINATION OF BARITE CONCRETIONS AND ENCLOSING MUD*

	Tubular Smooth Concretion		Round Smooth Concretion	Enclosing Mud
	inside	outside		
Al.....	X	X	X	X
B.....	0.0X	0.0X	0.0X	0.0X
Ba.....	XX	XX	XX	0.0X
Ca.....	XX	XX	XX	XX
Cr.....	0.0X	0.0X	0.0X	0.0X
Cu.....	0.0X	0.0X	0.0X	0.0X
F.....	—	—	—	X
Fe.....	X	X	X	X
Ga.....	0.0X	0.0X	0.0X	0.0X
K.....	0.X	0.X	0.X	X
Li.....	0.0X	0.0X	0.0X	0.0X
Mg.....	X	X	X	X
Mn.....	0.0X	0.0X	0.0X	0.0X
Na.....	X	X	X	X
Ni.....	—	—	—	0.0X
Pb.....	0.0X	—	—	—
Si.....	X	X	X	X
Sr.....	X	X	X	0.X
Ti.....	0.X	0.X	0.0X	0.0X

* Examination by Dr. T. G. Kennard. Tests were also made with negative results for the following elements: Ag, Au, As, Be, Bi, Cb, Cd, Ce, Co, Cs, Ge, Hf, Hg, In, Ir, La, Mo, Os, Pd, Pt, Rb, Re, Rh, Ru, Sa, Sb, Sc, Sn, Ta, Th, Tl, V, W, Y, Zn, Zr.

Explanation of Symbols:

XX	= large amount >10 per cent
X	= moderate amount 10–1 per cent
0.X	= small amount 1–0.1 per cent
0.0X	= traces only <0.1 per cent
—	= none found

Results

Barite content.—Barium sulphate in the analyzed concretions varies from 62 to 77 per cent (Table 3). Bjerrum's analysis of nodules collected by the SIBOGA expedition in the

PLATE 2.—SECTIONS OF CONCRETIONS

FIGURE 1.—POLISHED SECTION SHOWING CONCENTRIC ZONING IN THE TUBULAR SMOOTH CONCRETION SELECTED FOR CHEMICAL ANALYSES

Note the alternating light and dark bands in the outer shell. × 15

FIGURE 2.—THIN-SECTION UNDER CROSSED NICOLS OF CONCRETION SHOWN IN FIGURE 1

Note interference crosses of barite spherulites. × 100

FIGURE 3.—THIN-SECTION OF FLAT WARTY CONCRETION UNDER PLANE POLARIZED LIGHT

Dark-gray portions are calcite (note foraminiferal tests); white areas are plagioclase or holes in section; large black spots are glauconite; light-gray groundmass is barite. × 30

East Indies (Bøggild, 1916) gave 82 per cent $BaSO_4$. Jones (1887) guessed that the nodules from the sea bottom near Ceylon contained about 75 per cent $BaSO_4$. An analysis by Chukhrov (1937) of concretions from the Pliocene of the Kertch Peninsula shows 82 per cent $BaSO_4$. According to analyses by Nichols (1906) and Shead (1923), the sand barites of Oklahoma contain from 52 to 55 per cent $BaSO_4$. The concretions from the Cretaceous Moreno shale, previously mentioned, appear to have from 40 to 65 per cent $BaSO_4$, the higher percentage being from the pisolitic crust. The outside shell of the tubular smooth concretion analyzed by us also contains a higher percentage of $BaSO_4$ than the core.

Comparisons of concretions and mud matrix.—No barium was detected by chemical means in the mud matrix of the concretions. On the other hand, appreciable amounts of fluorine and phosphate were found only in the mud. These may be combined with calcium in the form of the mineral collophane. When a comparison of the concretions and the mud is made on a barite-free basis, several other differences are evident. The amounts of iron and alumina are much higher in the concretions than in the mud,

TABLE 3.—CHEMICAL ANALYSES OF BARITE CONCRETIONS

	Oklahoma Sand Barites		Kertch Nodules Chukhrov[9]	Kai Island Nodules Bøggild[4]	California sea floor concretions			
					Tubular smooth		Round smooth	Mud matrix
	Nichols[1]	Shead[2]			(Inside)	(Outside)		
SiO_2	36.99%	45.13%	9.41%	6.42%	9.87%	6.95%	10.81%	23.18%
Al_2O_3	5.36	0.88	5.56	2.32	3.99	3.76	4.39	7.16
Fe_2O_3	0.82	0.96	1.06	1.67	2.35	2.26	3.67	
MgO	0.03	0.00	0.65	0.42	0.97	0.48	0.98	1.80
CaO	0.51	0.00		2.01	4.40	4.21	8.38	29.40
BaO	35.76	34.25	53.22	53.85	47.92	50.96	40.91	0.00
Na_2O[5]					n. d.	n. d.	0.28	2.62
K_2O					n. d.	n. d.	1.66	0.58
SO_3	19.20	17.87	28.12	28.56	25.02[6]	26.42	21.33[6]	n. d.
P_2O_5			0.25		tr.	tr.	tr.	0.62
NaCl[7]					n. d.	n. d.	.76	2.21
F					n. d.	n. d.	n. d.	0.42[8]
CO_2[9]					0.86	1.78	5.77	22.03
H_2O	0.27	0.31	1.39	2.94	3.99[10]	2.97[10]	1.86[10]	3.49
Org. m.	0.32	0.00	n. d.					4.56
MnO		0.02	0.20					
TiO_2			tr.					
Total	99.26%	99.42%	99.86%	98.19%	99.28%	99.79%	100.80%	98.07%
$BaSO_4$[11]	54.41%	52.12%	81.88%	81.85%	72.94%	77.54%	62.24%	0.00%

1. See Nichols (1906).
2. See Shead (1923)
3. See Chukhrov (1937).
4. See Bøggild (1916).
5. Computed from total Na−Na required to balance Cl.
6. SO_3 computed from % BaO.
7. Computed from dissolved chloride determination.
8. Determined spectrographically.
9. CO_2 computed from acid soluble CaO.
10. Organic matter plus water equal loss on ignition minus computed CO_2.
11. $BaSO_4$ computed from % BaO.

whereas calcium carbonate is higher in the mud than in any of the concretions analyzed.

A considerable part of the calcium and strontium of the concretions was acid-insoluble and therefore could not have been present as a carbonate. It is possible that this acid-insoluble material was chiefly strontium sulphate. This possibility is supported by the results of an attempt to determine the amount of soluble sulphate in the concretions and in the enclosing mud using the conductimetric titration method of Anderson and Revelle (1947). Barium chloride was added to suspensions of the mud and of a powdered concretion and the end point was determined by a sharp increase in conductivity. The apparent amount of soluble sulphate relative to dissolved chloride was about twice as great in the concretion as in the mud. This would be true if $SrSO_4$, which is more soluble than $BaSO_4$, were present in the concretions. The barium added during the titration would not only precipitate with the dissolved sulphate ion but would also replace strontium in $SrSO_4$.

Even after allowance is made for sodium balanced against chloride, there are considerably greater amounts of sodium in the mud than in the one concretion in which alkalies were determined. Potassium, on the other hand, is more abundant in the concretion than in the mud. This reversal of the sodium-potassium ratios may indicate a replacement of the exchangeable sodium of the concretions with other cations.

Specific Gravity and Porosity

One to six gram fragments of different types of nodules were dried overnight at 105°C and weighed. Their volumes were determined by weighing the mercury that was displaced when the nodules were immersed in a mercury-filled pyknometer. The ratio of weight to volume was taken as the bulk specific gravity of the fragments. After being crushed, the samples were placed in a pyknometer filled with petroleum ether of determined specific gravity. The grain specific-gravity was taken as the ratio of the weight of the pulverized fragments to the volume of ether displaced. Duplicate determinations were made by the same procedure using kerosene as the immersion liquid.

Bulk specific gravities of the samples vary between 2.43 and 3.01, while the grain specific gravities range from 3.44 to 3.97. For comparison, pure barite averages 4.35. In contrast, the bulk specific gravity of the mud is only 1.13 and the grain specific gravity is 2.51. The measured grain specific gravities agree fairly closely with those computed from the chemical analyses (Table 4). The percentage of pore space, calculated from the difference between the bulk and grain specific gravities, is also shown in Table 4.

Table 4.—Specific Gravity and Porosity of Individual Concretions

Type of Concretion	Bulk Specific Gravity	Grain Specific Gravity	Calculated Grain sp. gr.	Porosity
Tubular warty	2.88	3.97		27.5%
Tubular smooth, outer shell	3.00	3.88	3.90	22.7
Tubular smooth, core	2.77	3.64	3.82	23.9
Tubular smooth	2.74	3.44		20.3
Round smooth	3.01	3.71		18.9
Round smooth	2.43	3.66	3.63	33.6
Flat warty, shelly	2.44	3.54		31.1
Irregular warty, partly shelly	2.99	3.47		13.8
Average	2.78	3.64		23.6
Enclosing med	1.13	2.51		54.9

Porosity is rather variable and high, ranging from 13.8 to 33.6 per cent and averaging 24 per cent. The average barium sulphate content computed from the specific gravities is 62 per cent by weight, or 50 per cent by volume. The volume occupied by barite plus the pore space equals 74 per cent, a value perhaps the same as the original porosity. While the actual measured porosity of the enclosing mud was only 55 per cent, a porosity of 74 per cent, which implies a water content of 52 per cent by wet weight, is well within the range of recent marine muds. The Moreno shale concretions, unlike those from the sea bottom, apparently have little or no remaining pore space, because their bulk specific gravity corresponds with the density computed from a rough chemical analysis.

By comparing the water contents of the

TABLE 5.—FORAMINIFERA IN CONCRETIONS AND ENCLOSING MUD*

Species	Age	Relative Abundance	
		Concretions	Mud
Angulogerina occidentalis (Cushman)			C
Angulogerina semitrigona (Galloway and Wissler)		C	
Bolivina acuminata Natland			R
Bolivina advena var. *striatella* Cushman			RC
Bolivina cf. *pisciformis* Galloway and Morrey	XXX	R	RC
Bolivina seminuda Cushman			RR
Bolivina sinuata Galloway and Wissler	XXX	R	RR
Bolivina spissa Cushman	X	R	A
Bolivina sp.	XXX		R
Bolivinita angelina (Church)	XX	C	
Bolivinita sp.	XXX		A
Bulimina cf. *affinis* d'Orbigny			C
Bulimina cf. *fossa* Cushman			R
Bulimina cf. *inflata* Sequenza	XX	C	A
Bulimina pagoda Cushman			R
Bulimina spinifera Cushman			RC
Bulimina subacuminata Stewart and Stewart			RC
Cassidulina californica Cushman and Hughes		C	
Cassidulina delicata Cushman	X	C	C
Cassidulina laevigata d'Orbigny			RC
Cassidulina lomitensis Galloway and Wissler		C	
Cassidulina quadrata Cushman and Hughes		A	A
Cassidulina tortuosa Cushman and Hughes		VA	
Cassidulina translucens Cushman and Hughes	XX	R	
Cassidulina tumida Natland			R
Cassidulina sp.	XXX	C	
Chilostomella ovoidea Reuss			RR
Cibicides cf. *basiloba* (Cushman)	XXX	C	R
Cibicides cf. *fletcheri* Galloway and Wissler		A	R
Cibicides mckannai Galloway and Wissler	XX	A	A
Cibicides repettoensis LeRoy	XX	VR	
Cibicides spiralis Natland	XX	R	
Discorbis rosaceus (d'Orbigny)		R	R
Ehrenbergina bradyi Cushman	X	VR	
Epistomina elegans (d'Orbigny)	X	VR	
Eponides frigidus (Cushman)		R	
Eponides subternera (Galloway and Wissler)			R
Eponides umbonata (Reuss)	XX	R	RR
Frondicularia advena Cushman			R
Glandulina laevigata d'Orbigny			R
Globigerina bulloides d'Orbigny		A	VA
Globigerina conglomerata Schwager			A
Globigerina inflata d'Oribgny			R
Globigerina quinqueloba Natland			VA
Globigerinoides minuta Natland			C
Globorotalia scitula (Brady)			C
Globorotalia truncatulinoides (d'Orbigny)			VR
Gyroidina soldanii var. *altiformis* Stewart and Stewart	XX	C	C
Lagena elongata (Ehrenberg)			R
Laticarinina pauperata (Parker and Jones)			R
Martinottiella communis (d'Orbigny)			R

TABLE 5.—FORAMINIFERA IN CONCRETIONS AND ENCLOSING MUD (*Continued*)

Species	Age	Relative Abundance	
		Concretions	Mud
Nodogenerina advena Cushman and Laiming	XXX		RR
Nodogenerina lepidula (Schwager)	XX	C	A
Nodosaria arundinea Schwager	XXX	R	C
Nodosaria hispida d'Orbigny		VR	
Nodosaria subsoluta Cushman	XX	R	
Nodosaria tosta Schwager	XXX	R	C
Nodosaria sp.	XXX		R
Nodosaria sp.	XXX		RC
Nonion pompiloides (Fichtel and Moll)	XX	A	VA
Nonion umbilicatula var. *pacifica* (Cushman)	X	R	A
Nonionella turgida (Williamson)			R
Orbulina universa d'Orbigny		C	A
Planulina aff. *ariminensis* d'Orbigny	XX		R
Planulina ornata (d'Orbigny)		C	A
Plectofrondicularia californica Cushman and Stewart	XXX	C	R
Pleurostomella sp.	XXX		R
Polymorphina charlottensis Cushman		R	
Polymorphina lactea (Walker and Jacob)			VR
Pseudoparrella pacifica (Cushman)	X	R	
Pullenia bulloides (d'Orbigny)	XX	R	RC
Pullenia salisburyi R. E. and K. C. Stewart		R	
Pyrgo serrata Bailey			RC
Sigmoilina tenuis (Czjzek)			C
Sphaerodina bulloides d'Orbigny			RR
Textularia flintii Cushman			R
Uvigerina ampullacea H. B. Brady			RC
Uvigerina canariensis d'Orbigny			R
Uvigerina peregrina Cushman	X	R	A
Uvigerina peregrina var.			A
Uvigerina senticosa Cushman	XX	VR	A
Uvigerina sp.	XXX	VR	R
Valvulineria araucana (d'Orbigny)	XX	VR	RC
Valvulineria inequalis (d'Orbigny)			R
Virgulina nodosa R. E. and K. C. Stewart			R
Virgulina schreibersiana Czjzek			R

* Age: X Known from Pliocene and only rarely in Recent sediments as shallow as the dredging.
XX Known from Pliocene but not Recent sediments as shallow as the dredging.
XXX Extinct and not present in rocks younger than Middle Pico, Pliocene.
Abundance: VA, very abundant; A, abundant; C, common; RC, rather common; RR, rather rare; R, rare; VR, very rare.

mud and of a concretion as calculated from the porosity with the total weight of chloride determined by chemical analysis, we find that the chlorinity of the interstitial water of the concretion is 33 parts per thousand, and the chlorinity in the mud is 27 parts per thousand. These values contrast with the usual chlorinity found in muds off the California coast, 19 parts per thousand.

FORAMINIFERA

Several specimens of the concretions and of the enclosing mud were examined for foraminiferal content by Mr. M. L. Natland, of the Richfield Oil Company. He distinguished 86 different species or varieties (Table 5). Of these, 26 were found in both concretions and mud, 17 in concretions alone, and 43 in mud alone.

Foraminifera of the mud were much easier to separate and study than those enclosed in the barite concretions, thus probably accounting for the large number of species found only in the mud.

According to Natland (1933), eight out of forty-three, or 19 per cent of all the species found in the concretions are now extinct and are not present in rocks younger than Middle Pico age (Upper Pliocene). Fourteen species, or 33 per cent definitely are not found in recent sediments at depths as shallow as that of the dredging in which the concretions were found, but do occur in Pliocene sediments. Seven other species, or 16 per cent are also present in the Lower Pliocene and only rarely occur this relatively shallow depth in recent sediments. Although the remaining 32 per cent of the species are found in recent sediments at the depth of the dredging, they are also present in Lower Pliocene sedimentary rocks. The Foraminifera of the enclosing mud have an age distribution essentially similar to that of the concretions.

From the foraminiferal evidence it is thus possible to conclude that the concretions were either formed in Pliocene sediments or in younger sediments consisting very largely of redeposited Pliocene materials. Formation of the nodules might have occurred during or after Repetto time (Lower Pliocene).

Occurrences of Barite in Sediments

Concretions from the Recent Sea Floor

Only two other occurrences of barite concretions in recent sediments dredged from the sea floor have been reported in the literature. This may reflect a real scarcity of such nodules, or it may be due to the small area of the ocean bottom represented in dredgings. The most widely known find is that made by the British surveying ship, Investigator, in 1235 meters off Colombo, Ceylon. According to Jones (1887), the nodules collected by the Investigator are irregularly rounded, varying in shape from almost spherical to roughly cylindrical. They range in size from 2 to 10 centimeters. The surfaces are said to be rough with small pits and protuberences. Barite is present as small radial aggregates, with glauconite and remains of Foraminifera and Radiolaria sparsely scattered throughout the concretions. Some of the shells of Foraminifera and Radiolaria enclose spherulites of barite. On the basis of a rough partial chemical analysis, Jones estimated that the nodules contain 75 per cent $BaSO_4$, together with small quantities of strontium and other elements. The specific gravity was determined as 3.77. No barium was detected by qualitative analysis of the mud that enclosed the nodules.

On the Dutch Siboga expedition to the East Indies in 1899 and 1900, barite concretions were dredged in blue mud from a depth of 304 meters near the Kai Islands. These concretions (Bøggild, 1916), have a maximum diameter of 6 centimeters. They are brownish-gray and are flat or irregular in shape with smooth surfaces. Some are compact; others are loose and porous. Many are hollow with an inside crust, or a geode-like lining of small barite crystals. The texture is fine-grained. Clay minerals, iron oxide, free silica or opal, and calcium carbonate of foraminiferal tests accompany the barite, which is present in amounts up to 82 per cent. The sample in which the barite nodules were found also contained concretions of iron sulphide.

From the descriptions and illustrations given by Jones and Bøggild, it is apparent that the concretions examined by them are similar in nearly every respect to those from the California sea floor. The nodules from off Colombo may be classed with our round smooth and tubular types, while those from off the Kai Islands belong to the irregular and flat groups.

Fossil Occurrences of Nodular Concretions

Occurrences of nodular barite concretions of various degrees of purity have been described by numerous authors from sedimentary rocks that range in age from Early Permian to Pliocene (Twenhofel, 1932).

Barite concretions of rounded, elliptical, or irregular form occurring in the Lower Permian of southwestern Oklahoma were mentioned by Tarr (1933) in a comprehensive discussion of barite rosettes from that state. These range from 1 to 8 centimeters in diameter and have either pitted or rough sandy surfaces. The concretions with pitted surfaces consist of pure

barite, occurring in a complicated structure of dominantly radial fibres, whereas those with rough sandy surfaces are massive and seem to be the result of cementation of sandstone. No suggestion as to the origin of the barite or the mode of precipitation was given.

From the Triassic of Bidston Hill, England, Moore (1898) described globular sand concretions the size of walnuts, which contain up to 34 per cent barite. Mackie (1901) cited the widespread occurrence of arenaceous barite nodules having as much as 37 per cent $BaSO_4$ scattered through the Triassic sandstone along the coast of Elginshire. Globular barite concretions with pitted and crenulated surfaces from the Upper Lias of France were mentioned by Collot (1905), who reported that previous authors had described them as remains of sponges and polyps.

The earliest reference to barite concretions of which we are aware is the mention by Georgi in 1798 of "Schwerspathbälle am Ufer der Sura und Piana" in the Jurassic of northeastern European Russia. These were later described by Samoilov (1917) together with other occurrences in Upper Jurassic and Cretaceous marine clays of a very large area. The barite appears in various forms, sometimes as nodules of characteristic shapes, elsewhere as a filling in marly septaria, and occasionally in phosphatic concretions. The widespread nature of the occurrences, all of the same geologic age, suggested to Samoilov that the barite had been deposited on the sea floor by a particular group of organisms which had flourished during later Jurassic time, and that the concretions had resulted from subsequent diagenetic concentration. Previously, Schulze (1905) and Thierfelder had shown that granules of $BaSO_4$ occur in the bodies of Xenophyophora, a group of marine rhizopods. These organisms are mostly confined to low latitudes, but range widely in depth, from 1 or 2 meters in coral reefs to more than 4000 meters. Samoilov thought that the observed presence of Xenophyophores in the ocean near Ceylon might be related to the finding in the same locality of the barite concretions described by Jones, and Andrée (1920) assigned the origin of the concretions collected by the SIBOGA Expedition to the activity of these organisms.

Rounded and slightly flattened sand barite nodules of Cretaceous age from the Libyan Desert were mentioned by Zittel in 1883. Pogue (1911) discussed the occurrence in the same general area of a few concretions of mammillary structure mixed with numerous barite rosettes. From California, barite nodules were reported by Anderson and Pack (1915), embedded in the Upper Cretaceous Moreno shale near Coalinga. Some characteristics of these nodules have already been mentioned.

Eocene concretions from the Yazoo clay of Louisiana were described by Hanna (1936). These have diameters up to 10 or 12 cm. and are composed of aggregates of pisolites consisting of nearly pure barite. The centers are commonly hollow with groups of irregular cavities which are free of foreign material. No mode of origin was suggested. In the Sahara Desert the Nubian sandstone, also Eocene, contains barite rosettes (Walther, 1912).

Delkeskamp (1900) published an extensive report on the marine Tertiary baritic sandstones of the Wetterau and Rheinhessen districts of Germany. Both rosettes and concretionary forms containing up to 80 per cent barite occur in the sandstones. Many of the concretions are spherical and possess a radial structure; others are irregular, with vegetable-like forms. Reis (1921) and Geib (1937) described the Middle Oligocene barite concretions from Steinhart in the Rheinhessen District, which were among those mentioned by Delkeskamp. These commonly have nuclei of molluscan shells or plant remains. Delkeskamp thought that ascending hot solutions containing barium had been forced to spread out through the sandstone because of the presence of an overlying impermeable layer of clay. Reis and Geib also assigned the origin of the barium to hot springs, but thought that the concretions were formed while the sediments were being deposited. According to Geib, the sulphate necessary for the precipitation of barium resulted from the decomposition of the soft parts of the molluscs whose shells were enclosed by the concretions. Several objections to this hypothesis are apparent. The most important is that the dissolved sulphate in the interstitial sea water of the marine sand would have sufficed to precipitate the barium.

Large concretions in Miocene marl of the

Lower Alps were mentioned by Collot (1905) who states that they are made up of radial aggregates of barite crystals.

Rounded, cylindrical, and irregular-shaped concretions containing up to 81 per cent barite from the Pliocene sedimentary iron ores of the Kertch Peninsula in Russia were analyzed and described by Chukhrov (1937). These nodules have a dense or finely crystalline structure, with veinlets of a lighter color and inclusions of öolitic iron ore, quartz, and clay. The surfaces are rough or mammillary. Chukhrov considered that the barite was originally present as a colloidal precipitate from which larger crystals later developed. As characteristic features of such metacolloidal barite, he lists: (1) rounded nodules having more or less smooth or tubercular surfaces, commonly with dehydration cracks; (2) cryptocrystalline texture, resulting in dense and earthy aggregates; (3) öolitic, pisolitic, concretionary, or septarian shapes; (4) mechanical admixtures and inclusions of materials other than barite; and (5) fibrous, radially arranged crystals formed principally from comparatively pure colloidal suspensions.

Other Types of Sedimentary Barite

Besides occurring as nodular or irregular concretions, barite is present in many other forms in sedimentary rocks. Perhaps the most spectacular are the barite rosettes and dollars, described by numerous authors including Tarr (1933) from the Lower Permian of Oklahoma; Pogue (1911) from the Cretaceous of Egypt; and Richardson (1923) from the English Lias. Veins and larger crystals of barite in lime concretions were mentioned by Martens (1925); similar occurrences in Paleozoic limestone and red beds were discussed by Dickson (1902) and Howland (1936). Barite cementing Triassic and other sandstones of England and elsewhere has been reported (Clowes, 1899; Greenwood, 1920), and barite crystals in pyritized ammonite shells were mentioned by Collot (1905). All of these authors believed that the barium had been carried to a point of deposition by percolating ground water which had previously encountered and leached barium-containing minerals or rocks. Little consideration was given to the mechanism of precipitation, except by Dickson and Tarr, who thought that the formation of barite occurred when the percolating ground waters containing barium ion mingled with other waters containing sulphate or came in contact with either gypsum or pyrite, which furnished the necessary sulphate.

Barite deposits in pipes carrying water from certain British coal mines were reported by Clowes (1889). Öolites and pisolites of barite apparently formed in oil wells by precipitation from brines have been described by many authors, among the latest being Barton and Mason (1925), while Hanna and Wolf (1934) reported fibres, öolites, and crystals of barite from the cap rock of Gulf Coast salt domes.

Stalactites, crusts, and mud consisting of barium and strontium sulphate have formed around a brine spring in a mine at Lautenthal in Hartz Mountains. Lattermann (1888) believed that the barium and strontium salts were precipitated by the mingling of the sulphate waters of the mine with the chloride waters, containing barium and strontium, of the spring. It is noteworthy that the concentration of chlorides in the spring waters is nearly three times that in sea water. Other deposits of baritic sinter around springs were reported from British coal mines by Dunn (1877) and from Colorado by Headden (1905). At the latter site, the sinter contained up to 94.6 per cent barite and was markedly radioactive.

Origin of Concretions from California Sea Floor

Characteristics requiring explanation

The following characteristics of the concretions from the California sea floor seem to be of genetic importance:

1. Localized occurrence on a probable fault scarp
2. Tubular shape of many of the concretions
3. Concentric zoning with higher barite content in outer shells
4. Warty surfaces and nipple-like protuberances
5. Probable greater permeability of flat concretions
6. Presence of fossil Foraminifera
7. Higher computed original porosity of concretions than measured porosity of enclosing mud
8. Relatively high content of strontium
9. Only traces of barium in enclosing mud
10. Abnormally high chlorinity of interstitial water in concretions

11. Lower sodium-potassium ratios in concretions than in mud
12. Lower silica-sesquioxide ratio in concretions than in mud
13. Brownish-gray color of some concretions, indicating oxidation

Concentration of Barite by Organisms

Samoilov in 1917 suggested that Xenophyophora, which are known to have skeletons containing barite granules, were responsible for the formation of concretions found off Ceylon. Andrée extended this suggestion to explain the occurrence of barite nodules off the Kai Islands. Xenophyophora are said to be widely distributed in the tropics, yet only three findings of barite concretions in dredgings are known, one of which, that off California, is outside the tropics. Had the barite of the nodules been originally deposited on the sea floor as the remains of these rhizopods, it would seem that a more wide-spread distribution of concretions would have resulted, and also that appreciable quantities of barite would have been present in muds enclosing the concretions. Moreover, analyses of the concretions from Ceylon and California show a relative abundance of strontium, only traces of which are associated with barite in the skeletons of the Xenophyophora (Schulze, 1905). Even if the original accumulation of barite had been carried out by these organisms, the tubular shape, zoning, and chemical contrast between the concretions and the mud would have required the subsequent migration and concentration of either dissolved or colloidal $BaSO_4$. This was, in fact, pointed out by Samoilov.

Chemical Precipitation from Sea Water

It might be supposed that chemical processes operating in the bottom muds could cause the precipitation of barium sulphate from sea water within or immediately above the sediment. Such precipitation would depend on whether the solubility product of $BaSO_4$ was exceeded. The concentration of barium in sea water is so low that it cannot be determined quantitatively by chemical methods. Since barium is utilized only to a slight extent by organisms, its concentration should bear a constant ratio to the chlorinity as do calcium and sulphate (Lyman and Fleming, 1940). According to Engelhardt's spectrographic examination (1936), the content of barium in sea water is less than 0.03 to 0.08 mg. per liter. He suggests that actually only a half to a tenth of this amount may be present. Taking a value of .005 mg./liter as the most probable one, and combining it with the known sulphate concentration of sea water, there is obtained an ion product for $BaSO_4$ of about $6\ (10)^{-10}$. Since the solubility product of $BaSO_4$ in pure water is about $1\ (10)^{-10}$, this would represent a six-fold supersaturation were it not for the lowered activity of ions in relatively concentrated salt solutions like sea water. The effect of lowered activity is shown by the approximately eight times greater solubility of calcium sulphate in sea-water than in pure water (Fraps, 1902). Barium sulphate itself is said to be about 15 times more soluble in magnesium chloride solutions of ionic strength equivalent to that of sea water than it is in extremely dilute solutions. It thus seems probable that the sea is only saturated or perhaps even undersaturated with $BaSO_4$. In order to cause precipitation, the content of either barium or sulphate must be increased over that prevailing in normal sea water. Such a concentration of sulphate is unlikely in the reducing environment of the bottom muds. Because of the small concentration of barium in the sea, all the barium from about 300 cubic meters would have to be extracted to form a concretion weighing a hundred grams and having 50 per cent barium sulphate. It is difficult to conceive of a motive force which would move such a large volume of water through a small space within the bottom muds. If this origin were effective, then the barite concretions would be a widespread phenomenon.

In 1901, Mackie proposed that the baritic nodules in the Triassic of Elginshire might have been formed by precipitation of barium sulphate during the evaporation of a saline lake. A similar origin was suggested by Meland (1922) for the barite rosettes of Oklahoma. Such a process off the California coast could have taken place only in a closed basin and therefore must have occurred long after the deposition of the muds, because the Foramini-

fera found within the concretions are typical of those of the open sea of Pliocene times. The barite might be expected to occur not as locally distributed concretions of various shapes but as thin crusts present over a wide-spread area. Other products of evaporation should be associated with the barite had the barium been concentrated in this manner, whereas none are present.

Cementation of Channels by Percolating Waters

Evidence for migrating solutions.—The tubular shape and the concentric zoning of many of the nodules might have originated through the cementation by barite of sediment surrounding a percolating channel. The flat type of concretion might likewise have been developed because of the greater permeability to migrating solutions offered by a thin shelly layer within fine-grained less pervious sediments. Nipple-like protuberances and possibly warty surfaces might have originated through the existence of a system of branching channels. The apparently higher original porosity of the concretions may indicate that moving waters swept out some of the fine-grained constituents of the mud from the channels. The apparently higher original porosity of the concretions may indicate that moving waters swept out some of the fine-grained constituents of the mud from the channels. On the other hand, this may be due to the cementation of a partially uncompacted sediment or to swelling accompanying crystal growth. The absence of barium in the mud indicates that the solutions must have come from an appreciable distance to the points of deposition. Strontium likewise must have been transported to the site, but, owing to its greater solubility, became more widely disseminated before precipitation.

Ground water.—Two types of migrating water may be considered: ground water and ascending juvenile water. Barite deposition from percolating ground water has been proposed by a number of writers as a probable mode of origin for many concretions found on land. If the concretions did originate in this manner, the ground water could not have been largely composed of sea water because of certain chemical characteristics of the concretions. The replacement of sodium by other cations, as shown by the reversal of the sodium-potassium ratio in the concretions as compared with the mud, could not have resulted from the action of sea water in which sodium is a predominant ion. Likewise, the calculated chlorinity of the interstitial water of both the concretions and the mud is much greater than that of normal sea water. Alumina and iron are present in extremely small quantities in sea water, yet these were concentrated in the concretions.

Owing to its high concentration of sulphate ions, sea water cannot dissolve or transport appreciable quantities of barium. Likewise, ground water from meteoric sources passing through marine sediments would probably acquire so much sulphate that it could not dissolve barium-containing minerals. Moreover, the localized occurrence of the concretions off San Clemente Island suggests that any ground water containing barium must have been very restricted areally.

Ascending hot solutions.—In our opinion, a reaction between ascending hot solutions and interstitial sea water of the sediments represents the most probable mode of origin of the concretions. The waters of some hot springs are known to contain appreciable quantities of barium chloride; in fact, many important deposits of barite are of hydrothermal origin (Emmons, 1918). Hot chloride solutions rising through marine sediments would come in contact with interstitial sea water high in sulphate ion, with the consequent precipitation of barium sulphate. Strontium, also commonly found in hot-spring waters containing barium, would have been in part precipitated with the barite and in part transported a greater distance because of the higher solubility of strontium sulphate. Highly concentrated chloride solutions such as those analyzed by Lattermann, might have been responsible for the increase in chlorinity of the interstitial water in the concretions and the adjacent mud. Alumina and iron could have been carried and deposited with the barium and strontium, while replaceable sodium and perhaps some calcium carbonate might have been removed by slightly acid waters in which sodium was not the predominant cation. Such waters could also have carried the radioactive materials present in the concretions. It is well known that ascending

hot solutions often escape to the surface in springs along faults, and thus a reasonable explanation is provided for the localized occurrence of the concretions along a probable fault scarp.

Possible Origin of Other Barite Nodules from the Ocean Floor

An interesting comparison may be made between the occurrence of the nodules off California and of those dredged from off Ceylon and off the Kai Islands. In each instance, the concretion locality is situated on or near a probable fault of considerable magnitude, which may have provided an avenue of escape of hot baritic solutions from magma to the surface. Although the exact locality of the concretions described by Jones is not known, the depth reported indicates that they occur along the straight steep slope bounding the western side of Ceylon. (See Feuille A IV of the Carte General Bathymetrique des Oceans, International Hydrographic Bureau, 1938.)

No modern soundings exist in the neighborhood of the locality from which barite nodules were dredged by the Siboga Expedition, but several facts indicate that this occurrence is in a zone of major earth movement. The following quotation is translated from Weber's footnote in French (1902) with reference to the station from which the nodules were dredged:

"To the north of the principal island of the Basse-Kei group an island has emerged from the bottom of the sea in historic times. This miniature island is situated on a sand bank and is surrounded by a coral bank which extends to Oed Island. The island consists of clay (and not of sand as is commonly the case with coral islands) and one finds also 'some stones, some traces of iron oxide, and fragments of ferruginous manganese'. This composition of the soil, although very remarkable for a coral island, corresponds perfectly in its nature to the bottom of the sea, which I have described. Even though this appears fantastic, I cannot refrain from pointing out this remarkable concordance".

Within a mile of the Siboga locality, the Challenger Expedition dredged

"several large concretions or fragments of a calcareous rock differing very considerably from the deposit (of blue mud). A section of these concretions resembled in most respects a section of a hardened globigerina ooze from tropical regions and near a continental shore. It is not improbable that these large concretions or rock fragments are hardened portions of a deep sea deposit formed at a much greater depth and subsequently elevated to the position in which they were found, probably by the the same elevation as that which upheaved the neighboring islands." (Murray and Renard, 1891)

The presence of major structural trends near the Kai Islands has also been pointed out by Kuenen (1935).

Summary

During the course of an investigation of the ocean floor geology off southern California, one of a large number of samplings encountered a submarine outcrop which consisted in part of barite concretions. These nodules are variable in size, shape, and surface character, as well as in bulk specific gravity. Many are concentrically zoned, with a hard outer shell surrounding a softer core. Petrographic examination shows that the barite is present chiefly as small radial aggregates of closely interlocking crystals often best developed inside the tests of Foraminifera. Most of the concretions include clay together with minor amounts of coarser detrital grains, but a few contain a much greater proportion of larger particles, chiefly plagioclase, glauconite, and foraminiferal tests. Spectrographic examination shows that barium and strontium are present in relatively large quantities in the concretions but in only minor amounts in the enclosing mud. Three chemical analyses of the nodules show the presence of 62 to 77 per cent $BaSO_4$, the highest amount being in the outer layer of a zoned concretion. The ratios of silica to sesquioxides and of sodium to potassium are lower in the concretions than in the enclosing mud. Bulk specific gravities vary between 2.43 and 3.01, while grain densities range from 3.44 to 3.97. Calculations based on these values show a porosity ranging from 14 to 34 per cent. The average barium sulphate content calculated from the specific gravity is 63 per cent by weight, or 50 per cent by volume. The bulk specific gravity, grain specific gravity, and porosity of the enclosing mud are respectively 1.13, 2.51, and 55 per cent. The calculated chlorinity of the interstitial water in the concretions is 33 parts per thousand, considerably higher than the normal chlorinity of bottom sea water. Examination of the tests of Foraminifera contained in the

concretions shows that 68 per cent of the species found do not occur on the present sea floor at the depth of barite outcrop and probably represent an early Pliocene fauna.

It is concluded that the nodules originated by a reaction between hot solutions ascending along a fault scarp and the interstitial sea water of the sediments. The ascending waters are thought to have carried strontium, aluminum, and iron, as well as barium, and to have been low in sodium and pH. A similar origin is suggested for the two other occurrences of barite nodules from the sea floor reported in the literature. This suggestion is supported by the fact that in each instance the concretion locality is situated on or near a fault of considerable magnitude which may have provided an avenue of escape of hot baritic solutions from magma to the surface.

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Manuscript Received by the Secretary of the Society, July 12, 1950

Contribution from the Scripps Institution of Oceanography, New Series, No. 510.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 62, PP. 725-744, 11 FIGS., 2 PLS. JULY 1951

ACCUMULATION AND ABLATION ON THE SEWARD-MALASPINA GLACIER SYSTEM, CANADA-ALASKA

By ROBERT P. SHARP

ABSTRACT

Upper Seward Glacier, an intermontane ice body, is the principal source of nourishment for Malaspina Glacier, a piedmont sheet on the southern Alaska coastal plain. The state of health and degree of activity of this system, covering 1650 square miles and involving about 420 cubic miles of ice, are best evaluated through records of accumulation and wastage.

Annual surplus in the accumulation area was 69 inches of water in budget year 1948–1949, 26 inches in 1947–1948, 17 inches in 1946–1947, and 30 inches in 1945–1946. A preliminary estimate for 1949–1950 is 30 inches, which is thought to be about normal under present conditions.

Daily gross ablation of firn in mid-summer on upper Seward Glacier ranged from a mean of 0.30 inch of water to a maximum of 0.87 inch. Ablation on the upper Seward in the summer of 1948 was 75 per cent greater than in 1949 over a corresponding period of 32 days. Daily gross ablation on clean Malaspina ice averaged 2.32 inches of water in 1949 or nearly nine times the rate on upper Seward Glacier.

As to material balance, 1948–1949 yielded a surplus of 9.01×10^{13} cubic inches of water owing to heavy accumulation and reduced ablation. Budget year 1947–1948 produced a deficit of 2.144×10^{14} cubic inches, more than counterbalancing the surplus of 1948–1949. Under existing climatological conditions even a normal year produces a deficit of about 2×10^{14} cubic inches. This glacier system is obviously in a poor state of health.

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Introduction

Introductory Statement

Accumulation is the life blood of a glacier, and its state of health can best be defined in terms of the relation between accumulation and wastage. In treating the material balance, or regime, of an ice body analogies with certain business terms and practices can be drawn. Each glacier is constantly striving to balance its income, in the form of total accumulation, against its expenditures in the form of total net wastage. Equilibrium is clearly the condition most desired by glaciers, and they differ from business in a positive abhorrence for profits. If a profit is shown, a glacier immediately expands in order to increase expenditures and bring them into balance with income. If a deficit occurs, recession follows until a balance is struck between wastage and accumulation.

The degree of activity of a glacier is best defined in terms of its total turnover, just as in business. A receding glacier may, nonetheless, be an exceedingly active glacier if the items of income and expenditure are large. It may also be a fast-moving glacier if large amounts of ice are being transferred from an area of surplus to an area of deficiency (Ahlmann, 1948, p. 59).

The practice has been to distinguish on each glacier an accumulation area, where accumulation surpasses ablation, and an ablation area where the reverse is true. Obviously, the accumulation area in April or May will be different from that in August or September. Therefore, Ahlmann (1946, p. 247) differentiates between temporary accumulation and ablation areas, as determined at any specified date, and annual surplus and deficiency areas as established at the end of the ablation season. The irregular patchy zone separating the surplus and deficiency areas is the firn limit. Glen (1941, p. 141) proposes a distinction between temporary firn limit, as determined by the conditions of a single year, and developed firn limit, as produced by the relations between surplus and deficiency areas over several years.

The concept of a budget year is also useful in treating glaciers. For the Seward-Malaspina system, the budget year can be satisfactorily defined as extending from that time in fall when accumulation first exceeds ablation in the surplus area to a time in the succeeding year when the same conditions attain. On some glaciers accumulation always exceeds ablation in the surplus area, so a budget year must be defined in terms of accumulation and ablation for the entire glacier. These relations may be difficult to determine, and a more useful definition can be made in terms of conditions at the firn limit, a new budget year being initiated when accumulation surpasses ablation at this location. Since accumulation plus ablation at the firn limit measures the total regime of a glacier with reasonable fidelity, as shown by Ahlmann (1948, p. 55) and confirmed by Wallén (1948, p. 560), this definition appears sound. The length of a budget year changes from year to year depending upon meteorological conditions.

Physical Setting

The Seward and Malaspina form one of the larger glacier systems of southern Alaska, covering at least 1650 square miles and containing an estimated 420 cubic miles of ice. This ice gathers largely in the heart of the Ice Field Ranges (Bostock, 1948, p. 98–100) of the St. Elias Mountains and flows southward to a coastal plain along the northern shore of the Gulf of Alaska where it spreads out to form a great piedmont sheet, the Malaspina Glacier (Fig. 1). The Malaspina covers approximately 1035 square miles[1] and is fed principally by the Seward, although it also draws substance from a number of local glaciers draining the southern slope of the St. Elias Mountains. The surface of the Malaspina rising from sea level to about 2000 feet is relatively smooth except for a peripheral belt 1–5 miles wide in which the ice is stagnant and has developed a rough superglacial topography with an extensive mantle of ablation debris. A vegetative cover growing on superglacial debris near the outer edge of the ice (Fig. 10) includes trees of Sitka spruce 100 years old. Parts of the Malaspina's surface display complexly deformed structures (Pl. 1, fig. 1) previously described and beautifully

[1] This figure was obtained by planimeter measurements on the International Boundary Commission map. The earlier and widely quoted figure of 1500 square miles given by Russell (1893, p. 224) was probably an estimate.

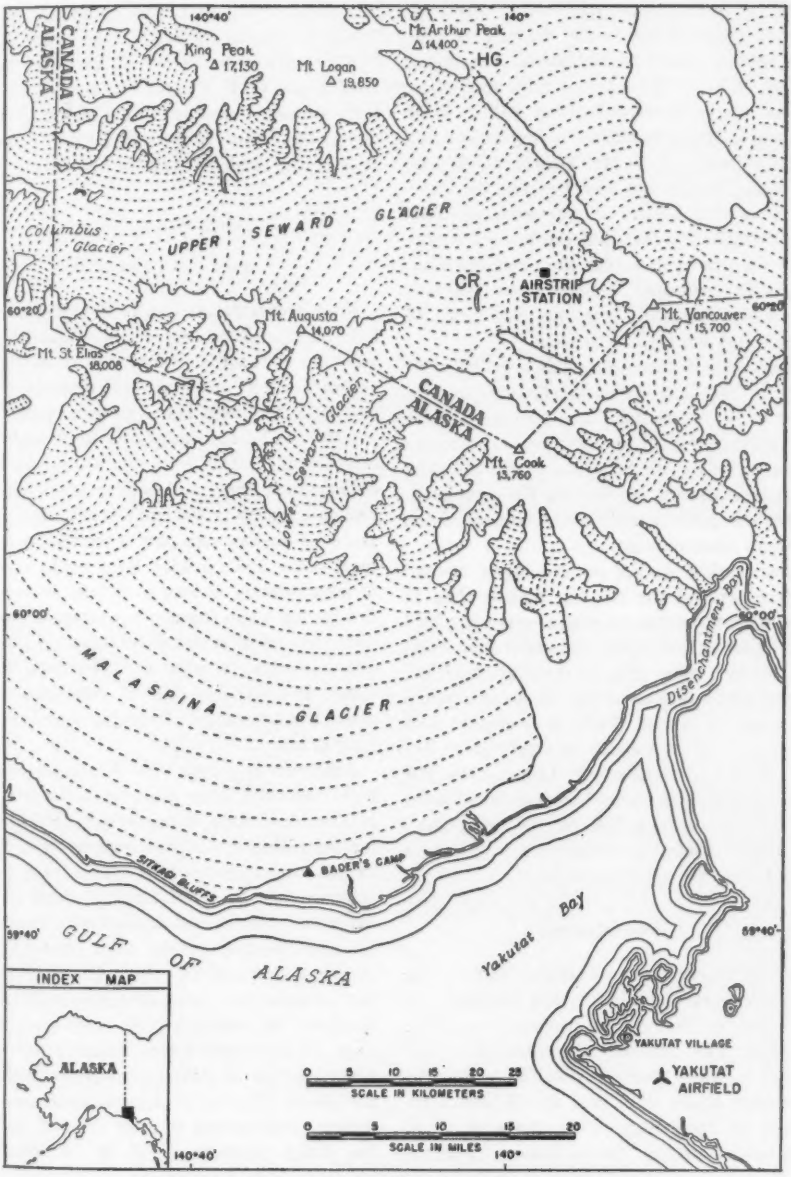

FIGURE 1.—MAP OF SEWARD-MALASPINA GLACIER SYSTEM
CR—Crud Ridge, HG—Hubbard Gap.

photographed by Washburn (1935, p. 1881–1884).

Seward Glacier consists of two principal parts; a large intermontane glacier (Matthes, 1942, p. 152) of approximately 515 square miles, herein designated the upper Seward, and

a narrow outlet glacier, the lower Seward, 20 miles long by 3–4 miles wide, discharging with high velocity into the Malaspina. The upper Seward with an extensive gently undulating surface ranges in elevation from 5000 to 7000 feet and is almost encircled by high peaks and ridges culminating in Mt. Logan, 19,850 feet (Pl. 1, fig. 2). The firn limit lies near the lower end of Seward Glacier at approximately 3000 feet altitude. The fact that the Seward constitutes the principal surplus area and the Malaspina the principal deficiency area of this glacier system greatly simplifies calculation of surplus and deficiency relations.

The upper Seward, although only 50 miles north of the Gulf of Alaska, has an environment more continental than maritime because of shielding afforded by high mountains to the south, including Mt. St. Elias, 18,008 feet. The Malaspina Glacier by contrast lies completely within the moist maritime environment of the southern Alaskan coast.

Glaciological studies on the upper Seward centered around the Airstrip Station (Fig. 1) 3 miles from the eastern edge at elevation 5875 feet. Observations on the Malaspina were made near Bader's camp (Fig. 1) at elevation 85 feet on the southern edge of the ice sheet about 5 miles east of Sitkagi Bluffs. Glaciological field work covered the periods of 3 July to 29 August, 1948, and 15 June to 29 August, 1949. The large C.A.A. airfield at Yakutat furnished a convenient operating base for the expedition's ski-wheel Norseman plane which provided transport to the field camps.

Acknowledgments

These observations constitute part of the scientific work of project "Snow Cornice", an endeavor of the Arctic Institute of North America. The glaciological studies were supported by the Office of Naval Research, the American Alpine Club, and the California Institute of Technology. The assistance of all members of project "Snow Cornice" and the wholehearted co-operation of its director, W. A. Wood, is acknowledged. Special appreciation is expressed for the aid of F. B. Leighton, L. H. Nobles, and G. P. Rigsby who participated in these studies. Personnel at the C.A.A. airfield and at the Libby, McNeill and Libby cannery at Yakutat rendered valuable assistance.

Accumulation

Nature of Accumulation

Most accumulation results from direct snow fall, but in places appreciable quantities of snow are introduced or removed by wind, and avalanches may produce local deposits of exceptional thickness. Hail can be a minor contributor, and under moist maritime conditions direct condensation from the air in the form of hoarfrost, rime, and similar arien deposits (Seligman, 1936, p. 49) can furnish a significant and even predominant part of the total nourishment (Glen, 1941, p. 137). Rain can be a source of accumulation as long as it falls on snow or firn having a sub-freezing temperature, for the water freezes as it percolates downward. Meltwater can also be refrozen under these conditions, and the freezing of rain water and meltwater are herein classed as secondary accumulation.

Attention is focused on the upper Seward and its environs since it serves as the principal accumulation area of this system. Snow is by far the chief form of nourishment here. Arien deposits are considered relatively insignificant because they have not been observed to any extent in summer and are probably restricted by continentality of the environment. Likewise, rain and hail are relatively unimportant, but considerable secondary accumulation is produced by refreezing of meltwater. That some wind drifting of snow occurs is shown by measurements of total accumulation in different places (Fig. 4), by accumulation recorded during windy storms in early summer, and by the direct observations of W. A. Wood in

PLATE 1.—MALASPINA AND SEWARD GLACIERS

FIGURE 1.—EASTERN PART OF MALASPINA GLACIER
Air view looking south, Pacific Ocean in background, 29 August 1948.

FIGURE 2.—AIRSTRIP STATION ON UPPER SEWARD GLACIER
Mt. Logan in background to northwest.

FIGURE 1

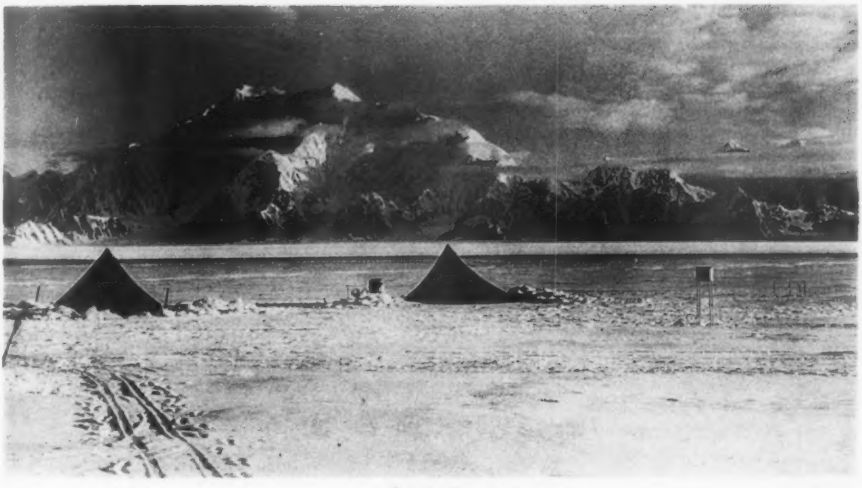

FIGURE 2

MALASPINA AND SEWARD GLACIERS

FIGURE 1

FIGURE 2

ABLATION MEASUREMENTS

March 1950. However, this is primarily a redistribution of snow precipitated onto the Seward Glacier, and vast areas of the firn are not particularly affected. The amount of snow actually imported or exported must be relatively minor owing to the encircling girdle of exceptionally high mountains.

Measurement of Accumulation

On upper Seward Glacier only the annual accumulation surplus has been determined, not the total accumulation for the entire year. Accumulation surplus for the current year can be measured by digging pits in various parts of the surplus area and measuring the thickness and density of the annual firn layer. Bulk densities were calculated from core samples of known weight and volume. If measurements are made at the end of the ablation season, and if allowance is made for the amount of ice in lenses, layers, and glands[2] within the firn, a reasonably accurate measure of annual accumulation surplus, both primary and secondary, is obtained. This is best expressed in terms of the equivalent amount of water.

Accumulation surpluses for earlier budget years can be determined by extending the pits to greater depths or by observations in crevasses. However, this procedure is not so simple as it sounds. Some difficulty arises in delimiting the various annual layers. Fortunately, in this area enough dirt usually accumulates on the firn by the end of the ablation season to produce a faint discolored zone. The firn of this dirty zone is also coarse-grained, porous, and of low density in comparison with surrounding material (Fig. 3). Although the debris is unquestionably air-borne, the impression is gained that much of it originates as a residual accumulation from the ablated firn and not simply as dirt blown onto the firn surface during summer.

In the vicinity of rock outcrops, debris-rich layers are prominent, numerous, and contain material clearly derived from the near-by rock. Some layers represent more than one year, as the excessive ablation near the rocks occasionally exceeds annual accumulation, and others are clearly without chronological significance, for they contain detritus so coarse that it must have been introduced by avalanches or mass wasting from the rock slopes. However, the faint discolored layers far out on the glacier, miles from rock exposures, are confidently regarded as annual because direct observation and markers buried by the 1948–1949 snow establish this relation for the discolored zone at the top of the 1948 firn layer, and it duplicates in all respects the underlying discolored zones.

Unfortunately, the discoloration produced in some years far out on the glacier is too faint to detect. In a 50-foot pit dug at the Airstrip in 1948 only the discolored zones of 1946 and 1947 were identified, although at least 10 annual firn layers were penetrated. Nor could dirty layers be recognized in the walls of crevasses near the Airstrip, but they were distinguished in narrow crevasses 6–6.5 miles southwest of the Airstrip near the outlet from upper Seward Glacier. In the walls of great gaping crevasses farther into the outlet many dirty layers, believed to be annual, could be seen from the air in proper light. Access to only one of these wide crevasses was gained on the ground, and the limited section exposed therein and in near-by narrow crevasses (Fig. 2) extends the accumulation record back to 1945–1946.

Other means of delimiting annual firn layers have not proved applicable. In June 1949, the 1948–1949 firn layer was of finer grain, lower density, and had fewer included ice bodies than the older firn beneath, but these differences disappear or at least are obscured after the first year. Ahlmann (1935a, p. 32–33, 35–36) concludes that certain extensive and continuous ice layers within the firn of Isachsen's Plateau (West Spitsbergen) are annual, and Sorge (1933, p. 339) distinguished successive annual firn layers at Eismitte in Greenland by differences in density. However, Wade (1945, p. 167) in Antarctica, and Moss (1938) in North

[2] Ahlmann's (1935a, p. 35) term is adopted for irregular vertical columns of ice in firn.

PLATE 2.—ABLATION MEASUREMENTS

FIGURE 1.—VON HUENE ABLATOMETER ON UPPER SEWARD GLACIER

FIGURE 2.—ABLATION STATION M-II ON MALASPINA GLACIER, 1949
Drilling hole for ablation dowel.

East Land (Spitsbergen), could not distinguish annual layers within the firn on any basis. On upper Seward Glacier, the prominent and extensive ice layers do not mark the tops of annual

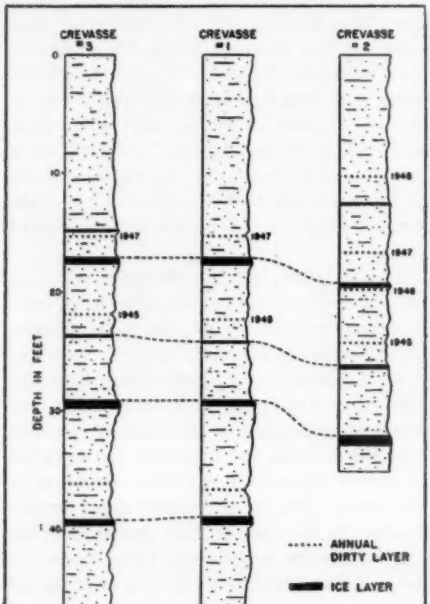

FIGURE 2.—CORRELATION CHART OF PROMINENT ICE LAYERS AND ANNUAL DIRTY LAYERS
Exposed in crevasses near outlet of upper Seward Glacier.

firn deposits (Fig. 2), and separation of older annual firn layers on the basis of density differences cannot generally be made.

Several factors must be considered with regard to the densities within annual firn layers used for calculating annual accumulation. If densities are measured in crevasses, the walls must be cut back to unaltered firn, often a difficult task. Even more troublesome is the allowance that must be made for increases of density and additions of ice in the form of layers and glands produced by refreezing of meltwater in firn more than one year old. This is secondary accumulation which is a real and bonafide factor insofar as the total economy of the glacier is concerned, but in comparing annual accumulation records it must be eliminated insofar as possible. This requires knowledge of thermal regimen and density changes within the firn from year to year. For reasons that cannot be detailed here, about 25 per cent of the density change in Seward firn is attributed to freezing of meltwater. This is an inexact figure, but it permits a crude correction of the annual accumulation surplus represented by older firn layers. Near the surface this correction is small and may be exceeded by errors in measurement of thickness or density, but it increases with depth and can become significant.

Correction of density values for transitory liquid water should also be made but is not possible from the available data. Fixed liquid water, when refrozen in winter, will of course contribute to secondary accumulation and is a relatively minor factor. These adjustments will have greater significance in accumulation studies more precise than those made on upper Seward Glacier.

Amount of Accumulation

Accumulation for the budget year 1948–1949 was determined at the Airstrip Station, at a point 3.5 miles N. 18° W. therefrom, and at a third location 6 miles S. 85° W. from the Airstrip (Fig. 6). Pits were dug on 28–29 August, 1949, at these localities, and densities were measured throughout the 1948–1949 firn layer (Fig. 4). Since the field party was evacuated on 29 August, before the ablation season ended, some estimate of ablation for the remainder of the season is required. In 1948 no ablation was recorded from 23 to 29 August, and weather records at Yakutat support the conclusion that the ablation season ended on 23 August, 1948. Comparison of Yakutat weather records for 1948 and 1949 suggests that ablation on upper Seward Glacier ended on or about 8 September, 1949. For purposes of estimating the final accumulation surplus, ablation is assumed to have continued for 10 days after 29 August at a rate of 0.5 inch (13 mm) of firn per day, which was about the average maintained for a week prior to 29 August. The accumulation as recorded at the three locations noted above and corrected for this additional ablation is recorded in Table 1.

The 66.1 inches (1679 mm) of water received at Airstrip Station and the 66.4 inches (1687 mm) 3.5 miles north-northwest therefrom are probably representative for most of the eastern part of the upper Seward. The 93.8 inches (2383 mm) 6 miles west of the Airstrip reflects exceptional accumulation in the lee of Crud Ridge, which is known to cause accumulation of wind-drifted snow, at least in early summer. A pit dug by F. B. Leighton in 1948 in a partly enclosed basin 14 miles north-northwest of the Airstrip showed an exceptionally heavy accumulation. This basin is also favorably situated for collection of wind-drifted snow, but such settings constitute a relatively minor part of the total area of upper Seward Glacier. Considering these facts an approximate adjustment is made for the areas of exceptional accumulation, giving an average figure of 69 inches (1753 mm) of water for the accumulation surplus on the eastern part of upper Seward Glacier for the budget year 1948–1949.

Accumulation surpluses of 24.5 inches (622 mm) of water for 1947–1948 and 16.1 inches (409 mm) for 1946–1947 have been determined from the thickness and density of the respective annual firn layers exposed in pits at the Airstrip. These values have been corrected for secondary accumulation occurring after the first year. A rough figure of 28.6 inches (726 mm) of water for 1945–1946 was obtained from the thickness of the annual firn layer exposed in an open crevasse 6.5 miles S. 45° W. from the Airstrip (Fig. 2) and from density measurements at the proper depth in firn at the Airstrip (Table 2). These figures will be more representative for the upper Seward if corrected for areas of exceptional accumulation and rounded off to the nearest whole number. Using a correction factor of 69/66.1 derived from the 1948–1949 accumulation, the results are 26 inches for 1947–1948, 17 inches for 1946–1947, and 30 inches for 1945–1946. A preliminary estimate for 1949–1950 of about 30 inches of water is obtained from a measurement of firn thickness on 20 March, 1950 by W. A. Wood and a study of Yakutat weather records.

Meteorological records at Yakutat show that the budget year 1948–1949 was one of abnormally heavy precipitation, 160 inches compared to a mean of about 135 inches, and also of low

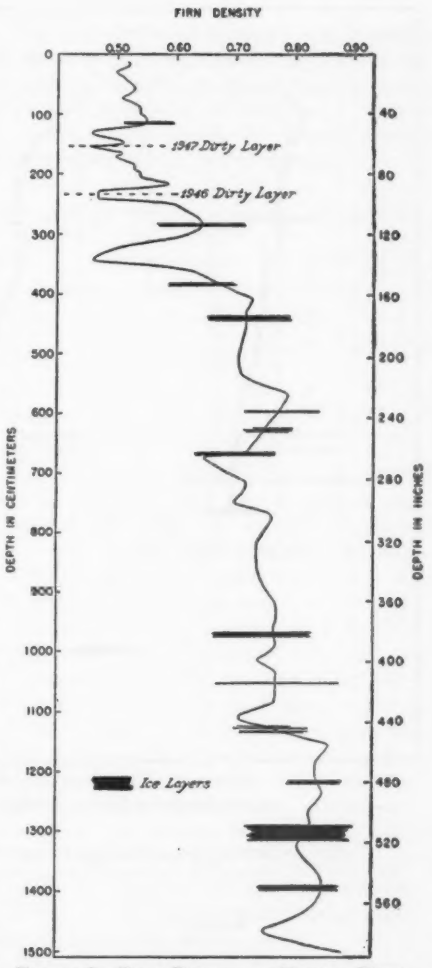

FIGURE 3.—BULK DENSITY OF FIRN IN DEEP PIT AT AIRSTRIP STATION, 1948

mean temperature, 36.7° F compared to a normal of about 40° F. These factors combined to make 1948–1949 an exceptional year, and the accumulation record on upper Seward Glacier bears this out. From the few data available, it is estimated that normal accumulation surplus on the upper Seward under present climatological conditions is 30–32 inches (762–813 mm) of water per year. Thus, the surpluses for budget years 1946–1947 and 1947–1948 were subnormal, that for 1945–1946 and the estimate

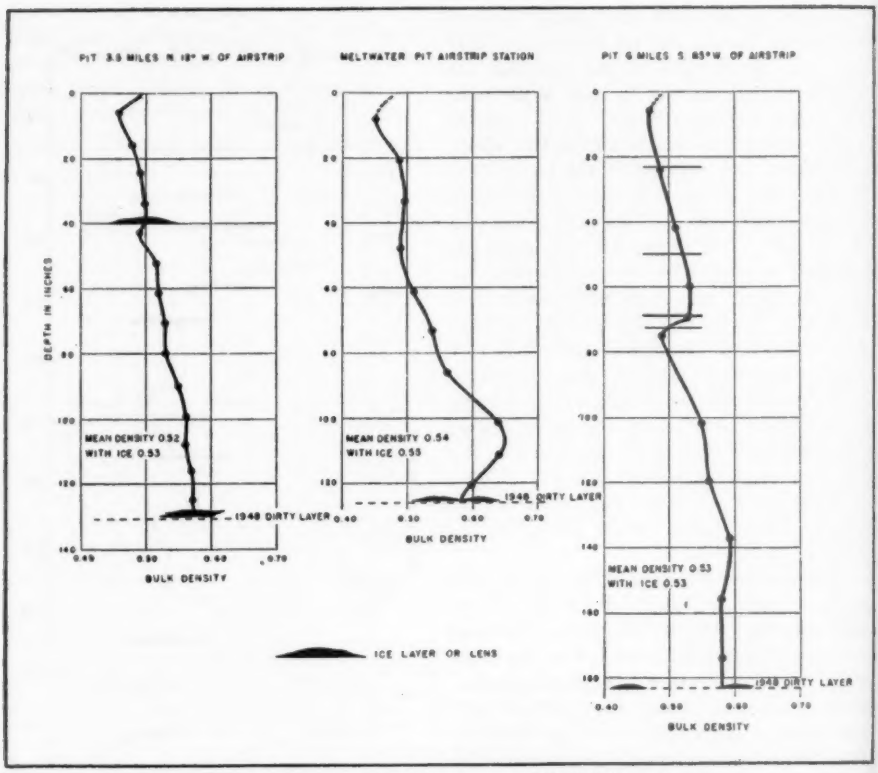

FIGURE 4.—THICKNESS AND DENSITY OF 1948–1949 FIRN LAYER
As determined in three accumulation pits on upper Seward Glacier, 1949.

TABLE 1.—ACCUMULATION SURPLUS ON EASTERN PART OF UPPER SEWARD GLACIER, 1948–1949

Location	Thickness of annual firn layer on 28–29 August, 1949, in mm	inches	Thickness, corrected for additional ablation in mm	inches	Mean density (including ice bodies)	Surplus as water in mm	inches
Airstrip Station	3200	126	3048	120	0.55	1679	66.1
3.5 miles N. 18° W. of Airstrip	3327	131	3175	125	0.53	1687	66.4
6 miles S. 85° W. of Airstrip	4648	183	4495	177	0.53	2383	93.8
Average, weighted for approximate areas represented by each location						1753	69

for 1949–1950 about normal, and that for 1948–1949 at least double the normal amount.

ABLATION

Introductory Statement

Ablation plays a significant role in glacier regime and exerts a major influence on temperature regimen and on the development of firn structures through its control of meltwater supply. It is hoped that future micrometeorological observations on upper Seward Glacier will permit a quantitative analysis and evaluation of various factors causing ablation comparable to that carried out in other areas (Sverdrup, 1935b; Ahlmann, 1935b; Wallén,

1948, p. 600–634). With the expectation that such studies will be made, an analysis of ablation on the basis of the insufficient meteorological data now available is not attempted.

For benefit of readers not well acquainted with glaciological literature the following brief notes on terminology are furnished. *Ablation* is the wastage of snow, firn, and ice by melting and evaporation. Ahlmann (1948, p. 26) extends the term to include calving and wind corrasion, thus making it practically synonymous with total or gross wastage, but it is preferred here to use ablation in the restricted sense. Internal ablation occurs in caves, crevasses, tunnels, and other englacial openings, but surface ablation is of principal concern in this report. *Gross ablation*, the total amount of melting and evaporation, usually exceeds *net ablation*, the amount of substance actually removed from the glacier by these processes, because meltwater is refrozen at depth to dissipate the winter's chilled layer. This difference can be appreciable, for net ablation is roughly 70 per cent of gross ablation on Isachsen's Plateau in West Spitsbergen (Sverdrup, 1935a) and 78 per cent on Kårsa Glacier in Sweden (Wallén, 1948, p. 529–530). With regard to glacier economics, net ablation, or more properly net wastage, is the significant figure, but gross ablation is more important in thermal regimen, formation of ice layers and glands, and circulation of meltwater in firn. Accurate measurement of net ablation is fraught with many difficulties (Ahlmann, 1946, p. 244–256).

Table 2.—Accumulation Surplus at Airstrip Station on Upper Seward Glacier, 1945 to 1949

Budget year	Thickness of firn in mm	inches	Mean bulk density	ected bulk density	Surplus as water in mm	inches
1948–1949	3048	120	0.55	0.55	1679	66.1
1947–1948	1219	48	0.51 (1948)	0.51 (1949) (no change recorded)	622	24.5
1946–1947	787	31	0.54	0.52	409	16.1
1945–1946	1346	53	0.57	0.54	726	28.6

Equipment and Procedure

The usual practice in rough determinations of gross surface ablation is to set a stake or pole deeply enough into the snow, firn, or ice so that it has no independent movement. Lowering of the surface is measured with respect to marks on this pole. The accuracy of this procedure is limited by irregularities on the surface, by local ablation around the pole, and by compaction settling within the material between the surface and the base of the pole.

In 1948 and 1949 daily determinations of gross ablation at the Airstrip Station were made on three one-meter sticks shoved 50 cm into the firn. Measurements are best made against such sticks by means of a card or stiff steel tape placed on the surface so that it carries the average level across the scale. Even with care, differences of several millimeters can result depending upon the way this is done. The meter sticks were reset each evening to reduce the effects of local ablation and to minimize the influence of compaction settling. As a check against the sum total of daily ablation readings, a permanent ablation pole or poles should be set at the same location. No such pole was used at the Airstrip in 1948, but one was established in 1949, and it is now concluded that no less than three permanent poles should be set to give best results.

Differences in the amount of daily ablation recorded on the meter sticks, all within a few feet of each other, were surprisingly large on occasions. The differences make one skeptical of short-period ablation measurements on a single marker, although over an extended period the variations seem to average out. In 1948, ablation was also measured on five large stakes set in a 225-degree arc with a half-mile radius around the Base Nunatak (Fig. 5). The readings, covering a period of 29–32 days, were reasonably consistent in comparable settings and strengthen the impression that variations in daily ablation as recorded on the meter sticks do cancel each other.

In 1949, five ablation stations were established on the eastern part of upper Seward Glacier in addition to the Airstrip Station. These straighten and reset the poles. In 1949, the ablation stations were not visited frequently enough, and the measurements suffered some-

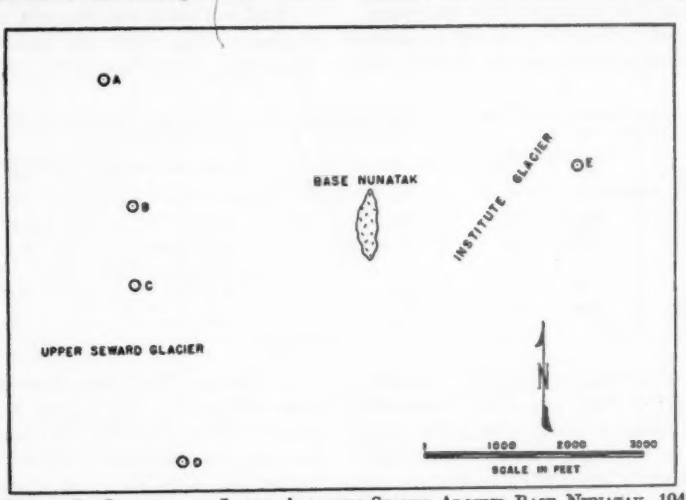

FIGURE 5.—LOCATION OF LARGE ABLATION STAKES AROUND BASE NUNATAK, 1948

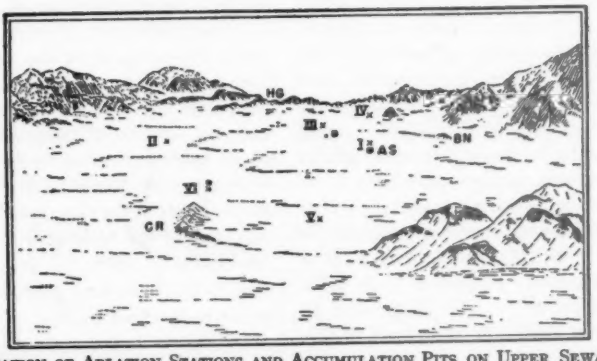

FIGURE 6.—LOCATION OF ABLATION STATIONS AND ACCUMULATION PITS ON UPPER SEWARD GLACIER IN 1949

BN—Base Nunatak, AS—Airstrip Station, CR—Crud Ridge, HG—Hubbard Gap x—ablation station ▪—accumulation pit. Sketched from high oblique air photograph looking north from southern edge of upper Seward Glacier.

were located in widely separated spots (Fig. 6) to obtain data on ablation in various environments and situations. At each ablation station three 6-foot bamboo poles were shoved as deeply into the firn as possible, usually 3.5–5 feet. Experience indicates that three poles is none too many and, further, that, in environments like those of the Seward Glacier, the stations should be visited fortnightly to what owing to leaning of the poles because of differential ablation. The figures obtained, in error possibly by 10 per cent, give minimum rather than maximum values.

For more accurate measurements over short intervals an ablatograph devised by Devik has been used by Ahlmann (1935b, p. 44; 1946, p. 239) and Wallén (1948, p. 562–566). This apparatus employs a float resting continuous

on the surface and consequently experiencing some independent movement because of differential ablation. To avoid, if possible, the various corrections that must be applied to measurements obtained by the Devik ablatograph, Rudolph von Huene constructed an ablatometer (Pl. 2, fig. 1) employing a movable spider which can be lowered onto the surface for a brief interval while measurements are being made and then withdrawn. The various features of this apparatus, and its mode of operation, are shown and described in Figure 7. Although the von Huene ablatometer promises greater accuracy than the Devik ablatograph, it requires more attention and does not yield a continuous record.

Tests of the von Huene ablatometer by L. H. Nobles in 1949 indicate that it can operate reasonably well under some but not all conditions. Little trouble was experienced in returning the spider to exactly the same spot on the firn, but it must be chilled before being brought into contact with the surface in order to prevent differential melting. The spider also produced indentations 1–2 mm deep when the surface was excessively soft or had a thin fragile crust. This effect can be reduced or eliminated by an alteration in design reducing the bearing pres-

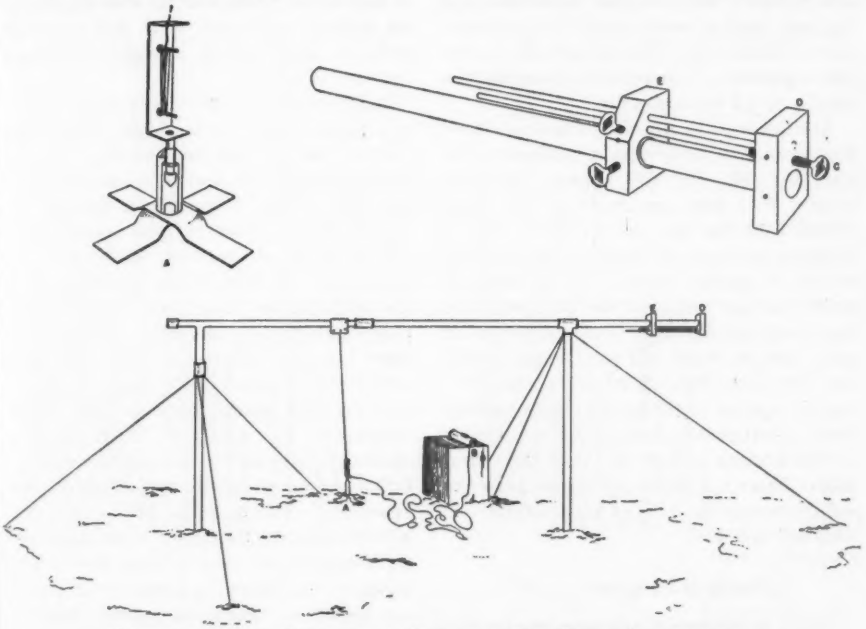

FIGURE 7.—SKETCH ILLUSTRATING DETAILS OF VON HUENE ABLATOMETER

This apparatus employs a light metal spider which can be raised and lowered, settling always to the same spot on the firn. The difference in the length of line played out gives a direct measure of ablation for the interval between observations. In making a measurement, the chilled metal spider (A) is lowered gently onto the firn until contact is well established as shown by completion of the electrical circuit and lighting of the flashlight (B). The spider is then lifted slowly by means of thumb screws (C) to the point where the electrical contact begins to break as indicated by flickering of the flashlight. Record is made of the separation between the inside surfaces of blocks, D and E, as measured by an inside micrometer with an accuracy of 0.1 mm. The spider is lifted free from the surface and buried in a near-by pile of firn in preparation for a later measurement. In practice the spider was usually lifted free by hand as soon as the position of break in the electrical contact was established, so it did not rest on the firn for more than a few moments. Using the point of break in the electrical contact established the same degree of tension on the braided linen fish line in each instance. Subsequent tests in the laboratory under various conditions of temperature and humidity show that change in length of this line are sufficiently great to require that some other type of line be used.

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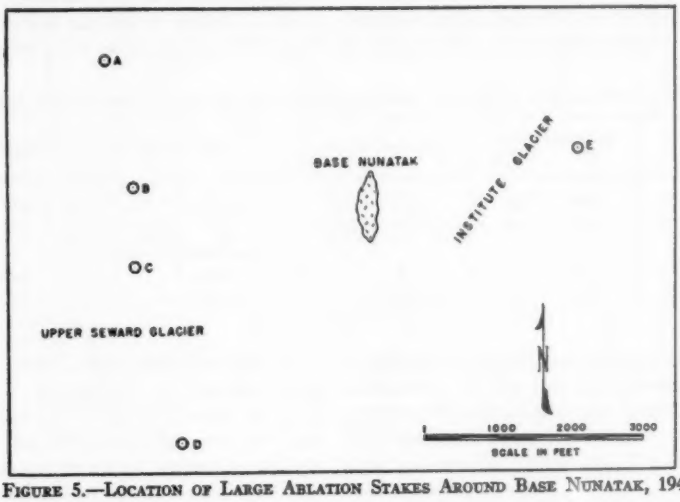

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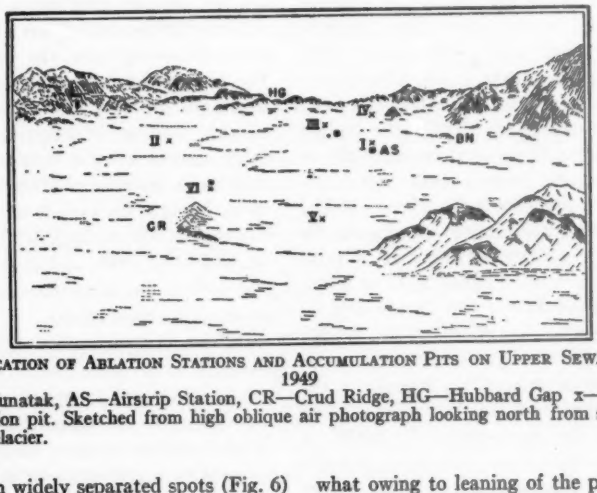

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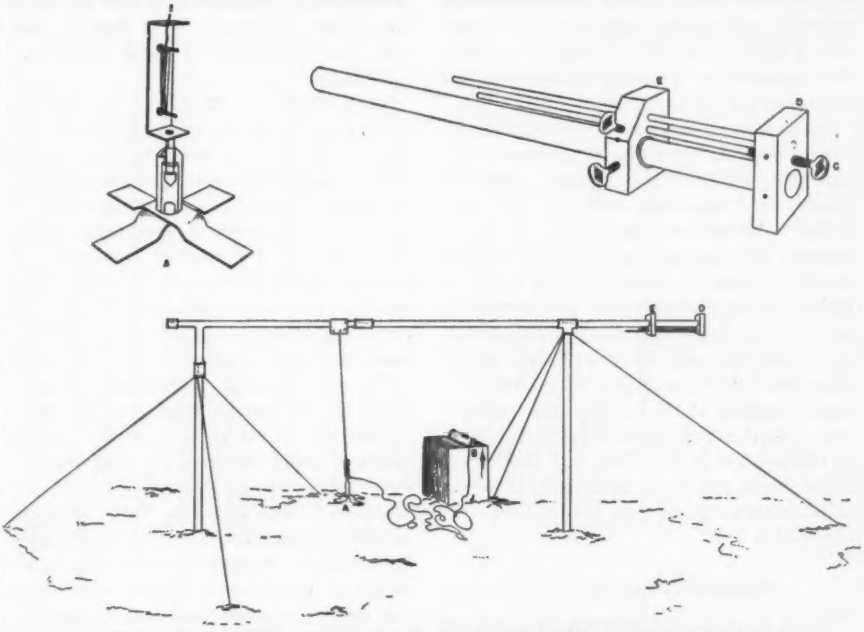

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sure of the spider. When set up, the ablatometer was firmly anchored to 4- by 4-inch posts driven 7–8 feet into the firn, and it was so oriented as to cast no shadow on the spot of measurement. With various precautions and due care, readings were repeated with a consistency of 0.2–0.7 mm. With further refinements, this apparatus can probably measure ablation reliably to 0.2–0.3 mm of firn.

Ablation was also recorded on areas of debris-free ice near the outer edge of Malaspina Glacier (Fig. 10). For this purpose, hardwood dowels, 9–12 feet long, were set into holes drilled 8–10 feet into the ice (Pl. 2, fig. 2). Ablation was measured against marks on these dowels. A possible source of error would be melting at the bottom of the hole permitting the dowel to sink deeper. Since the dowels are poor conductors and still fitted snugly against the sides of the holes after being in place for a month, melting at the bottom seems unlikely. Only a short-period measurement was obtained at one location in 1948, but, with the help of Henri Bader and Bruce Robertson, better results covering 36 days at two stations were obtained in 1949.

Ablation Measurements in 1948

Owing to the unavoidably late date at which they were initiated, observations of ablation on the Seward firn for 1948 are incomplete and have value chiefly as indicating the amount of gross ablation at the height of the season and as recording ranges in daily ablation.

At the large stakes (Fig. 5) on the Seward firn in areas remote from complicating influences of bedrock exposures, gross ablation averaged 0.28 inch (7.1 mm) of water per day over a period of 30 days extending from late July to late August. Daily ablation at the stake on Institute Glacier (Fig. 5) for this same period averaged 0.30 inch (7.6 mm) of water; the higher rate presumably reflects its location in a valley with large exposures of bedrock within 0.5 mile. Temperatures recorded at the Base Nunatak near this stake were nearly always higher than at the Airstrip, 2.5 miles out on upper Seward Glacier and 350 feet lower. Daily gross ablation of firn at the Airstrip over the interval between 12 July and 23 August averaged 0.30 inch (7.6 mm) of water. This value, somewhat higher than that recorded at the large stakes on Seward firn, reflects the influence of periods of exceptionally warm clear weather with strong ablation between 12 and 26 July before the large stakes were set. If only the ablation subsequent to 25 July is considered, the daily Airstrip average is 0.26 inch (6.5 mm) of water.

Daily ablation at the Airstrip from 12 July to 3 August, 1948, can be plotted in two ways (Fig. 8)—first as total melt including both firn and new-fallen snow, and second as gross ablation solely of firn. Some melting probably occurred during periods of snow accumulation, but no means of evaluating this factor were devised, and it represents a possible error in the total melt as plotted. Total melt for this period amounted to 10.4 inches (264.2 mm) of water and gross ablation of firn to 6.2 inches (157.5 mm) of water. With respect to glacier economy, the second figure has the greater significance. For conversion of the measurements to water equivalents a bulk density of 0.50 was assumed for firn and of 0.20 for new-fallen snow. The figure for firn is reasonably reliable, although the density of the uppermost layer changes considerably from time to time owing to variations in liquid water content and to diurnal freezing and thawing (Sverdrup, 1935a, p. 86). Wallén (1948, p. 530) shows that the bulk density used in such calculations is a controlled estimate at best. The density assumed for new-fallen snow is less reliable because of the variability of this material and the rapid changes in density that it can undergo. The value assumed is the approximate mean of possible extremes, and the total precipitation recorded at the Base Nunatak indicates that it is not far wrong. Settling within new-fallen snow also complicates measurement of its ablation.

Maximum gross ablation of firn during the period of daily observation in 1948 occurred on 17 July and attained 0.87 inch (22 mm) of water (Fig. 8). Greater total ablation was recorded on 19 and 21 July and 29 August, but much of the material wasted on these dates was new-fallen snow.

From 23 to 29 August, 1948, no measurable ablation occurred at the Airstrip. Weather records from upper Seward Glacier and from Yak-

utat for August and September also suggest that the 1948 ablation season on upper Seward Glacier ended on 23 August.

In 1948, ablation on debris-free Malaspina ice about 2 miles from the glacier's margin was recorded for only 44 hours. The 24-hour average for this period was 3.3 inches (83.8 mm) of water, assuming an ice density of 0.90. This was an interval of exceptionally clear, warm weather, and the high rate of ablation, compared to the 1949 measurements, can be attributed to this fact.

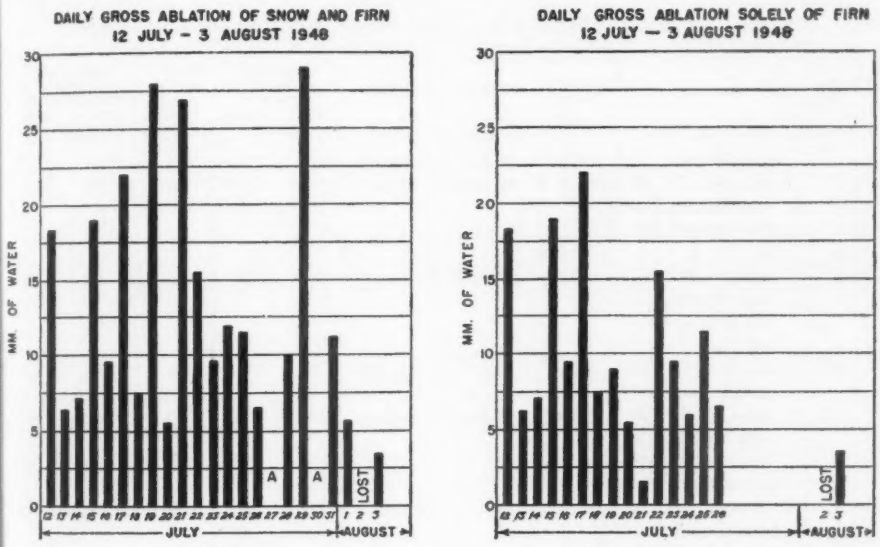

FIGURE 8.—GRAPHS OF DAILY ABLATION AT AIRSTRIP STATION IN 1948
Accumulation exceeded ablation on days marked A. Material ablated between 27 July and 1 August was new-fallen snow.

Ablation Measurements in 1949

The records of 1949 are more detailed and cover a greater area as well as a longer interval (16 June–29 August) than in 1948. Data from six ablation stations (Fig. 6) in the eastern part of upper Seward Glacier are compiled in Table 3. Average daily gross ablation of firn ranges from 0.21 inch to 0.39 inch (5.33–9.91 mm) of water, and the average for all six stations is 0.27 inch (6.86 mm). The maximum value, from Station V near the outlet gap of eastern Seward basin (Fig. 6), reflects elevation, lower than the average by 370 feet, and a shorter interval of measurement which included the period of most intense ablation of the 1949 season. The minimum value, from Station III, is presumably a product of greater elevation. The higher rate at Station IV, with a still higher elevation, is attributed to its location in a cirquelike basin, with high rocky walls to the east and north, and to the particular part of the ablation season measured, 4 July–16 August.

If consideration is restricted to ablation during July and August, the most effective part of the 1949 ablation season, the 0.25 inch (6.35 mm) of water per day recorded at Station VI is the most representative. The lower figures at Stations I, II, and III include the greatly reduced ablation of firn during late June (Fig. 9).

Daily gross ablation was observed at the Airstrip Station in 1949 as described, and these data are plotted as total ablation, including new-fallen snow, and as ablation solely of firn (Fig. 9). Total ablation during the last half of June attained 2.13 inches (54 mm) of water, but ablation of firn alone amounted to only

0.44 inch (11 mm). Ablation of firn became significant only after 1 July. Unlike 1948, however, it was continuing at a good rate when the field party was evacuated on 29 August. Weather records from Yakutat suggest that the 1949 ablation season on upper Seward Glacier extended to 8 September.

TABLE 3.—ABLATION AT STATIONS ON EASTERN PART OF UPPER SEWARD GLACIER, 1949

Station no.	Location	Elevation in feet	Period of observation	Total gross ablation of firn as water in mm	Total gross ablation of firn as water in inches	Period of observation in days	Average daily gross ablation of firn as water in mm	Average daily gross ablation of firn as water in inches
I	Airstrip Station	5875	16 June–29 August	442	17.4	75	5.84	0.23
II	9 miles N. 57° W. from Airstrip Station toward Mt. King	5925	19 June–21 August	356	14.0	64	5.59	0.22
III	7 miles N. 18° W. from Airstrip Station toward Hubbard Gap	6125	19 June–21 August	343	13.5	64	5.33	0.21
IV	6 miles N. 9° W. from Airstrip Station	6160	4 July–16 August	333	13.1	43	7.87	0.31
V	6 miles S. 45° W. from Airstrip Station toward Seward Outlet	5540	3 July–15 August	414	16.3	42	9.91	0.39
VI	6 miles S. 85° W. from Airstrip Station toward Crud Ridge	5840	30 June–28 August	371	14.6	59	6.35	0.25
Average for all							6.86	0.27

In 1949, the maximum daily gross ablation of firn (0.61 inch (15.5 mm) of water) was recorded on 3 August. This is considerably less than the 0.87 inch (22 mm) maximum recorded in 1948. The 0.77 inch (19.6 mm) of water indicated for 23 June, 1949, involved only new snow and may be in error because of improper density assumption. Maximum hourly ablation measured by the von Huene ablatometer ranged from 0.1 to 0.12 inch (2.5–3 mm) of water. As in 1948, meteorological data are not of the proper type and detail to permit an evaluation of ablation processes. In general, greatest ablation occurred on warm days with a thin overcast which returned much of the outgoing radiation to the firn surface.

The early appearance and excellent development of ablation features on the firn surface in 1948, the greater number of open crevasses, and the large amount of water standing in crevasses suggest that ablation during 1948 was greater than in 1949. This is confirmed by the ablation records; the 0.25 inch (6.35 mm) daily ablation at Station VI in 1949 during the height of the season falls well below the 0.28–0.30 inch (7.1–7.6 mm) recorded in 1948 at the Airstrip. Total ablation at the Airstrip from 12 July to 22 August, 1948, was 12.7 inches (323 mm) of water, and during the corresponding period of 1949 it was only 7.2 inches (183 mm).

Two ablation stations were established on areas of bare ice near the southern edge of Malaspina Glacier. Station M-I occupied a patch of coarsely crystalline, blue ice at elevation 660 feet, about 2.5 miles northwest of Bader's camp (Fig. 10). The area surrounding this station was thinly mantled with bouldery ablation debris. Station M-II (Pl. 2, fig. 2), at elevation 750 feet about 0.5 mile farther northwest, occupied a prominent mass of clean,

coarsely crystalline, bubbly ice. Thin patches of ablation debris were scattered sparsely over the ice surrounding this location. These stations, established on 15 July, were observed at intervals extending to 20 August.

water per day recorded in 1948 on Malaspina Glacier and 3.6 inches of water on Hayden Glacier (Tarr, 1909, p. 82), are considerably higher, but they represent observations of such short duration that the figures of 1949 must

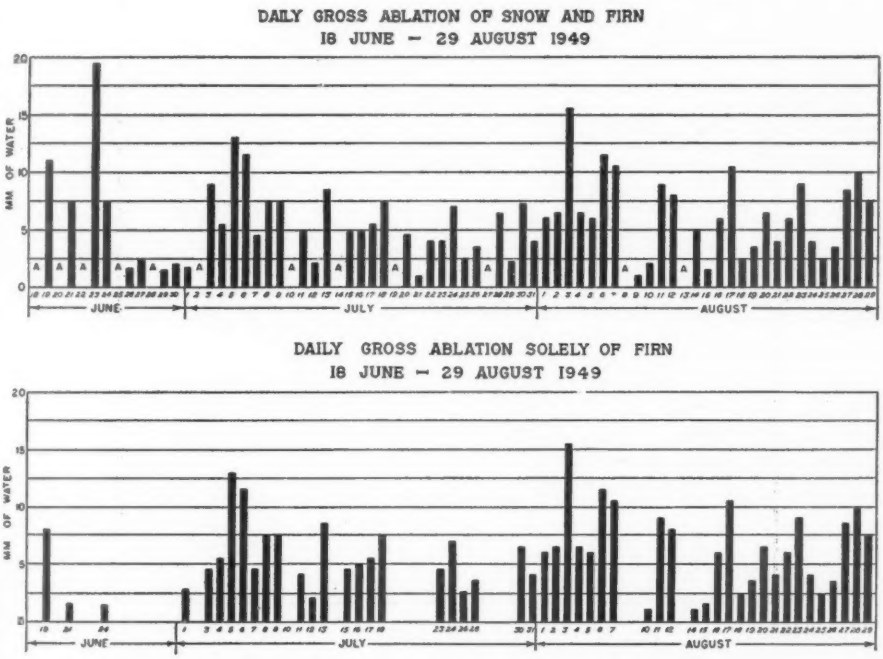

FIGURE 9.—GRAPHS OF DAILY ABLATION AT AIRSTRIP STATION IN 1949
Accumulation exceeded ablation on days marked A. No ablation of firn occurred on some days owing to accumulation or ablation of new snow.

Table 4 shows that ablation was slightly greater at M-I than at M-II for the entire period and that average daily ablation rates were 2.36 inches (60 mm) and 2.28 inches (58 mm) of water respectively. The average daily rate did not change greatly over the period of observation. These figures are for gross ablation which is probably identical with net ablation in these locations at this time of year.

The slight difference in ablation at the two stations is a product of differences in elevation, the amount of near-by superglacial debris, and the somewhat greater albedo of white bubbly ice at Station M-II. The only other ablation figures for this environment, 3.3 inches of

take precedence. More significant is the fact that the rate of ablation on Malaspina Glacier in 1949 was nearly nine times that on upper Seward Glacier.

SURPLUS AND DEFICIENCY RELATIONS

Introductory Statement

Data are not complete enough to permit calculation of regime as defined by Ahlmann (1948, p. 49) in terms of total accumulation and total wastage. However, a rough calculation of accumulation surplus above the firn limit and of excess wastage in the deficiency area is possible, and the state of health of this glacier system is indicated by the relation be-

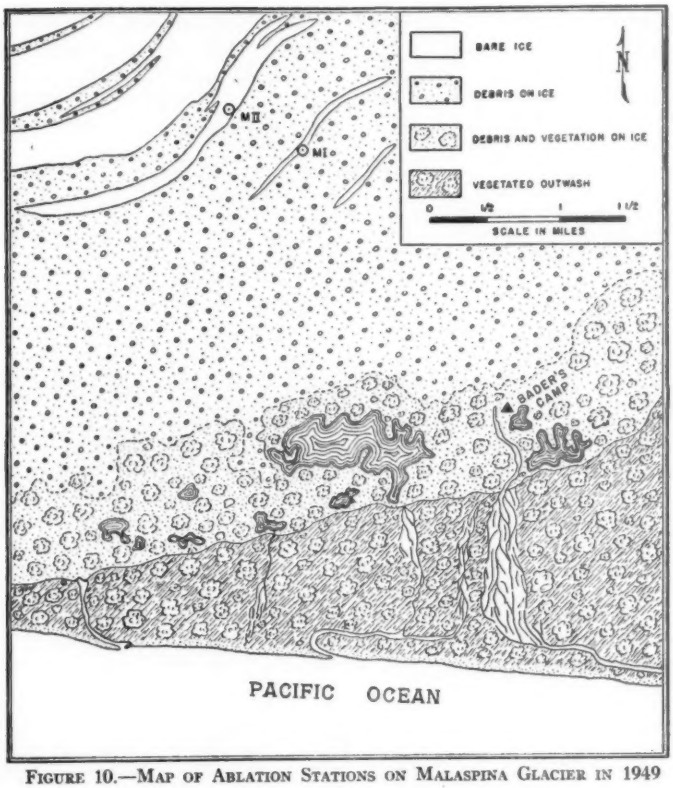

FIGURE 10.—MAP OF ABLATION STATIONS ON MALASPINA GLACIER IN 1949

TABLE 4.—MALASPINA ABLATION READINGS IN 1949

Station No.	Elevation in feet	Gross ablation from 15 July to date indicated, in mm and inches of water						Daily average gross ablation as water in	
		to 27 July		to 7 August		to 20 August		mm	inches
		mm	inches	mm	inches	mm	inches		
M-I	660	720	28.4	1429	56.3	2158	85.0	60	2.36
M-II	750	686	27.0	1290	50.9	2079	81.9	58	2.28

tween these items. The Seward Glacier and only that part of the Malaspina Glacier fed by it are considered. Fortunately, this huge system is dominated by two principal elements of such size and uniformity that a reasonable estimate of the surplus and deficiency items is possible from relatively few measurements. This is so because the principal source of nourishment, upper Seward Glacier, is a great ice body of nearly featureless surface and relatively uniform environment, and the principal wastage area, Malaspina Glacier, is a piedmont sheet with a gently sloping surface and a modest range in altitude. The problem is further simplified by the fact that the part of Malaspina Glacier fed by the Seward can be delimited easily on air photographs and maps by its moraines.

Material Balance

The accumulation surplus for this system in the budget year 1948–1949 is calculated as

TABLE 5.—MATERIAL BALANCE OF SEWARD-MALASPINA GLACIER SYSTEM

Accumulation Surplus Above Firn Limit

	Area in square inches	Mean accumulation surplus in inches of water per unit area	Accumulation surplus in cubic inches of water	Total accumulation surplus in cubic inches of water
1948–1949				
Upper Seward Glacier	2.065×10^{12}	69	1.425×10^{14}	
Glaciers Tributary to upper Seward basin	2.645×10^{11}	75	1.985×10^{13}	1.935×10^{14}
Remaining upper Seward watershed	8.23×10^{11}	20	1.646×10^{13}	
Lower Seward Glacier and tributaries	4.21×10^{11}	35	1.472×10^{13}	
1947–1948				
Upper Seward Glacier	2.065×10^{12}	26	5.37×10^{13}	
Glaciers tributary to upper Seward basin	2.645×10^{11}	30	7.93×10^{12}	7.533×10^{13}
Remaining upper Seward watershed	8.23×10^{11}	10	8.23×10^{12}	
Lower Seward Glacier and its tributaries	4.21×10^{11}	13	5.47×10^{12}	

Wastage Deficit Below Firn Limit

	Area in square inches	Mean ablation in inches of water per unit area	Wastage deficit in cubic inches of water	Total wastage deficit in cubic inches of water
1948–1949				
Snow-free and debris-free ice of Malaspina supplied by Seward	5.23×10^{11}	160	8.37×10^{13}	
Debris-covered ice	9.23×10^{11}	16	1.477×10^{13}	1.034×10^{14}
Internal Wastage	5 per cent of total surface ablation		0.492×10^{13}	
1947–1948				
Snow-free and debris-free ice of Malaspina supplied by Seward	1.745×10^{12}	150	2.62×10^{14}	
Debris-covered ice	9.23×10^{11}	15	1.39×10^{13}	2.897×10^{14}
Internal wastage	5 per cent of total surface ablation		1.38×10^{13}	

Material surplus (+) or deficit (—) in cubic inches of water

1948–1949	$+ 9.01 \times 10^{13}$
1947–1948	$- 2.144 \times 10^{14}$

follows. The mean surplus of 69 inches of water obtained from the three accumulation stations (Table 1) in eastern Seward basin is assumed to be representative for the entire upper Seward Glacier with its area of 515 square miles. Errors introduced by this assumption probably do not exceed 10 per cent. Planimeter measurements on maps of the International Boundary Commission show that ice streams flowing into upper Seward Glacier from surrounding slopes have an aggregate area of 66 square miles. No figure is available for the annual accumulation surplus represented by these bodies, but it is probably somewhat higher than on the upper Seward, owing to greater elevation and reduced ablation, and is estimated at 75 inches of water. The remaining 205 square miles within the upper Seward watershed con-

FIGURE 11.—DIAGRAM OF MATERIAL BALANCE RELATIONS ON SEWARD-MALASPINA GLACIER SYSTEM

sists of bare-rock slopes or immobile mantles of ice and snow which supply substance to the upper Seward Glacier largely by avalanches and wind drifting. A conservative estimate of the surplus derived from these slopes is 20 inches of water. The area of lower Seward Glacier and its tributaries is 105 square miles, and the accumulation surplus is estimated at 35 inches of water since this area extends from the upper Seward with its 69 inches to the firn limit with no surplus near the end of lower Seward Glacier. Totalling all sources of supply (Table 5) yields a surplus of 1.935×10^{14} cubic inches of water for the year 1948–1949.

Calculation of excess wastage on that part of Malaspina Glacier fed by the Seward is more difficult and more inaccurate. A considerable part of this ice is covered by ablation debris, and its rate of wastage is a subject of estimation. The glacier is riven with crevasses and subglacial openings in which an unknown amount of internal ablation occurs, and from which subglacial streams carry fragments of ice. Furthermore, measurements of ablation were made near the southern edge of the ice sheet and cover only a part of the ablation season, the total length of which must be estimated from Yakutat weather records. In the face of these difficulties and uncertainties, an estimation of excess wastage may seem foolhardy. Nonetheless, it is attempted because, even though crude, this estimate gives an indication of the state of health of this glacier system.

Ice supplied by Seward Glacier constitutes an area of 665 square miles in the Malaspina as determined by planimeter from the International Boundary Commission map. Air photographs show that 35 per cent of this area, or 230 square miles, is debris-covered; the remaining 435 square miles is bare ice except when covered by snow. The 1948–1949 snow mantle on the Malaspina was exceptionally thick and long-lasting. Even at the end of August, 70–75 per cent of the total Malaspina surface was snow-covered, and it is estimated that not more than 30 per cent of the debris-free, Seward-supplied ice in the Malaspina was free of snow by the end of the ablation season. Observations from the air showed that the ablation season on this ice did not start before 15 June, owing to a complete snow cover, and meteorological records at Yakutat suggest that

a new blanket of snow did not develop on the Malaspina until well into November. On this basis, maximum duration of the ablation season on debris-free ice is estimated at 160 days, but during this period the snowline recedes slowly across the ablation area. Ice at the outer edge of the ablation area is exposed for the entire 160 days, but ice farther inland is exposed for progressively shorter periods down to a day or two at the firn limit. Therefore, the mean ablation period for the entire ablation area is taken at 80 days. The mean rate of ablation on debris-free ice for 36 days during the height of the season near the southern edge of the Malaspina in 1949 was 2.32 inches of water per day. From this figure a mean of 2 inches of water per day is assumed for debris-free ice for the mean duration of the ablation season. Ablation under a debris cover is many times slower and varies with the thickness and nature of the mantle. It is arbitrarily taken at 10 per cent of the rate on bare ice. Internal wastage is estimated at 5 per cent of the total surface ablation. From these estimates, the total deficiency on Malaspina Glacier for the budget year 1948–1949 is calculated at 1.034×10^{14} cubic inches of water (Table 5). Subtracting this from the total accumulation surplus leaves a net surplus of 9.01×10^{13} cubic inches of water for the Malaspina-Seward glacier system in the budget year 1948–1949.

A similar calculation is attempted for the budget year 1947–1948 when accumulation surplus on upper Seward Glacier was 26 inches of water, and the Malaspina Glacier lost most of its snow mantle by middle July. These calculations are also summarized in Table 5, but the control is less reliable than for 1948–1949. Accumulation surplus for 1947–1948 was 7.533×10^{13}, the wastage deficiency 2.897×10^{14}, and the material deficit a huge 2.144×10^{14} cubic inches of water. Estimates of wastage on Malaspina Glacier for 1947–1948 are possibly too high, but even so it appears that an exceptionally favorable year such as 1948–1949 fails to provide a material surplus compensating the huge material deficit produced by a slightly subnormal year such as 1947–1948. This suggests that the average year, with an accumulation surplus of about 30 inches of water in upper Seward basin and with ablation on Malaspina Glacier reduced somewhat from 1948, fails to produce a balanced budget. Even in the average year under existing climatological conditions this glacier system may show a deficit in the neighborhood of 2×10^{14} cubic inches of water. Its state of health is not good.

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Manuscript Received by the Secretary of the Society, August 23, 1950.

GEOLOGIC MAP

OF

CALVERT FORMATION AND PAMUNKEY GROUP

IN

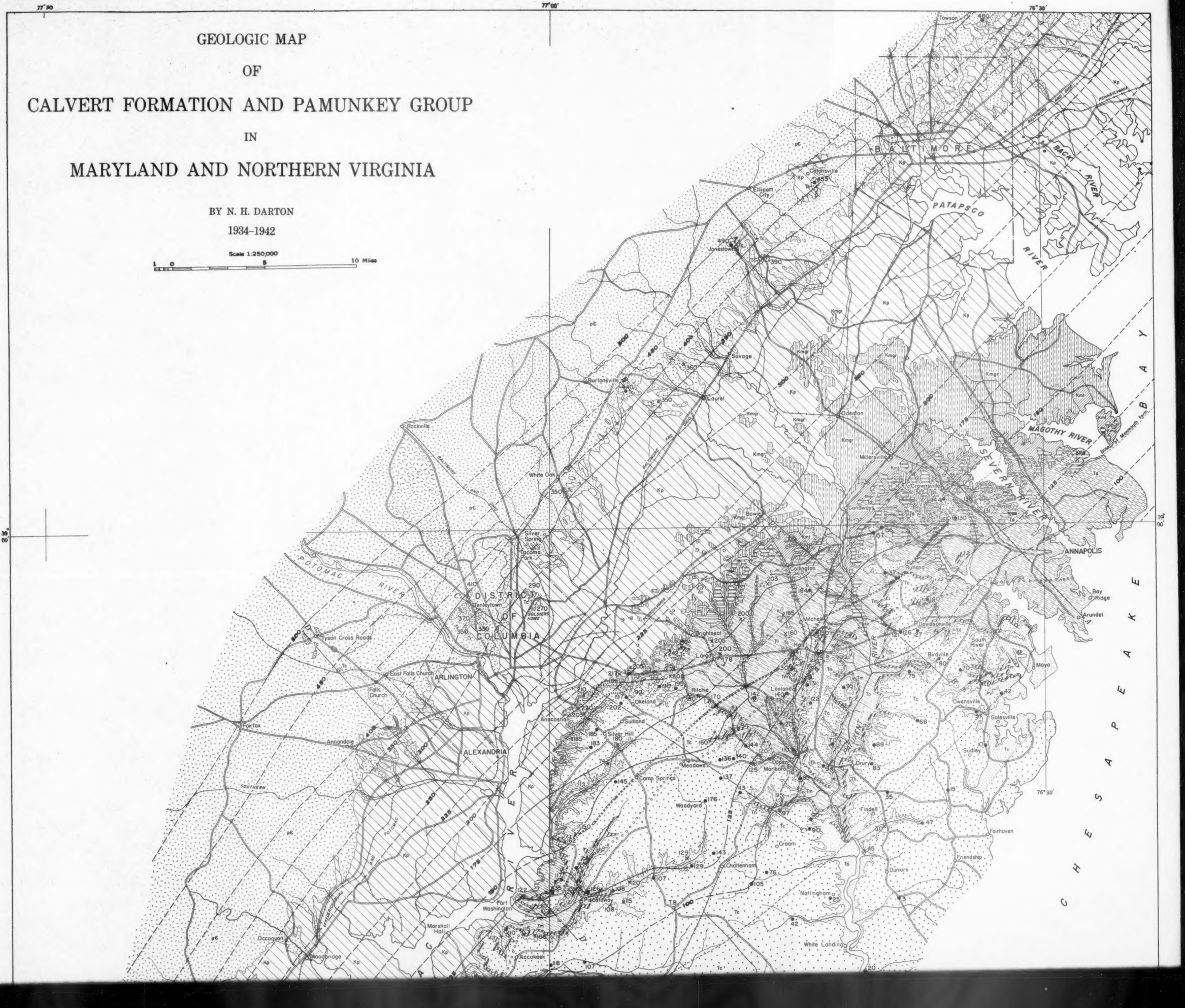
MARYLAND AND NORTHERN VIRGINIA

BY N. H. DARTON

1934–1942

Scale 1:250,000

1 0 5 10 Miles



NKEY GROUP

VIRGINIA

10 Miles

77°00'

76°30'

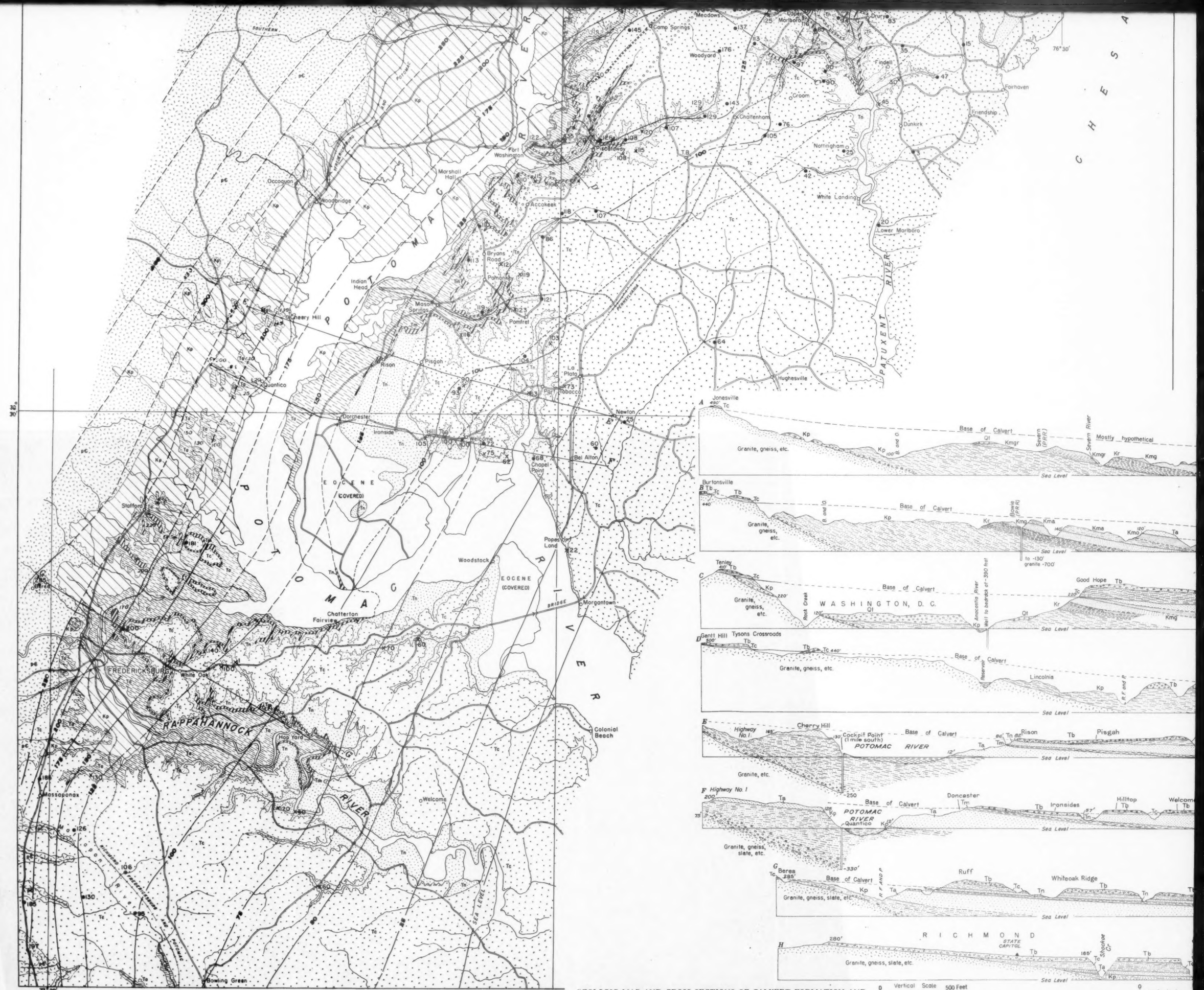
39°00'

EXPLANATION

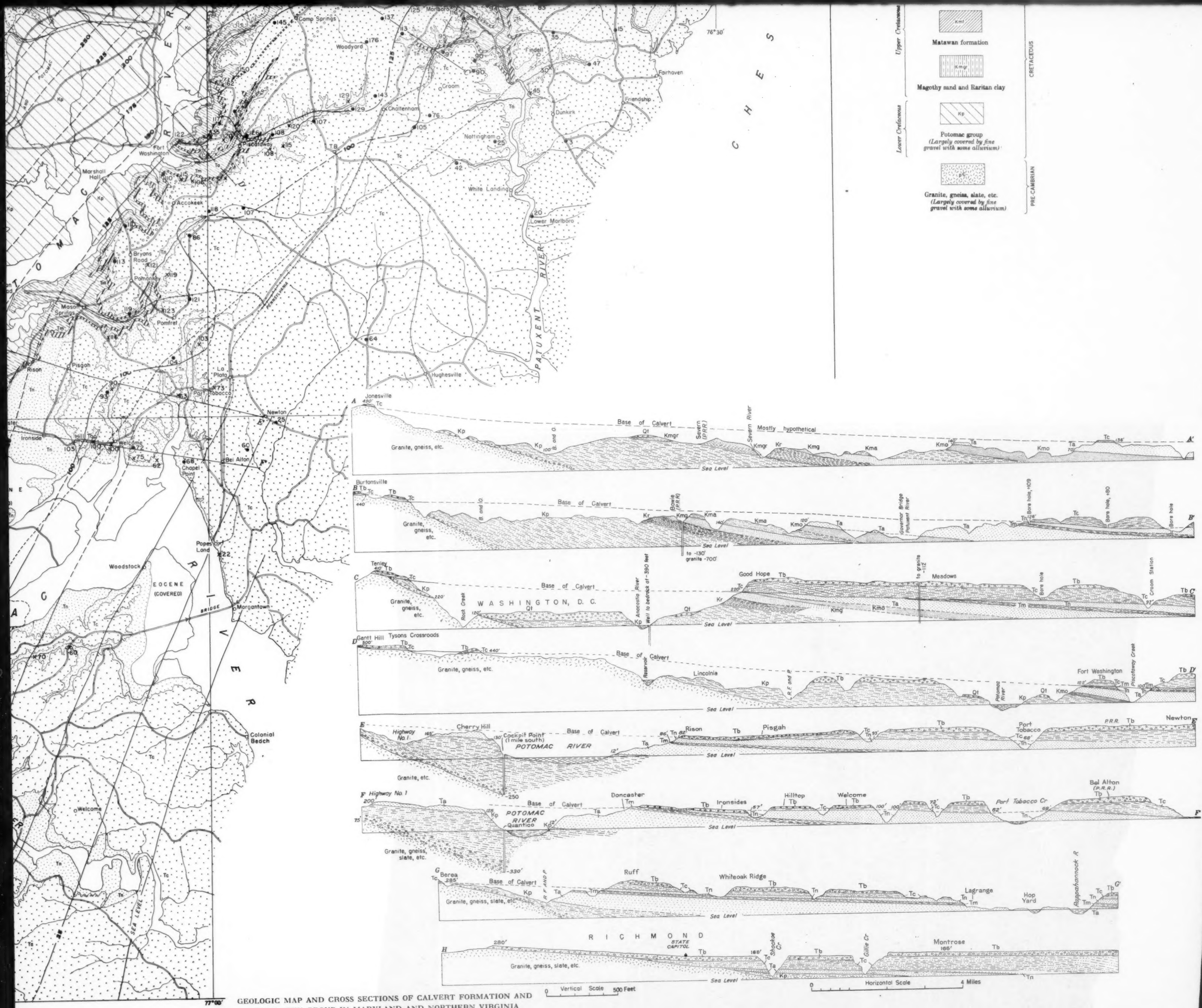
- Tc — Calvert formation *(Covered by Brandywine formation in high plateau areas)*
- 300 — Structure contours drawn on base of Calvert formation *(Contours from sea level to 500 feet. Dashed where hypothetical)*
- × — Basal contact of Calvert formation exposed with altitude
- • — Basal contacts of Calvert formation in bore holes with altitude
- Tn — Greensand member
- Western margin of Greensand at overlap
- Tm — Marlboro clay member *(Mostly Pink)*
- Top of Marlboro clay member at sea-level
- 132 — Altitude at top of Marlboro clay member
- Western margin of Marlboro clay member at overlap
- To — Aquia formation *(Mostly Greenstone)*
- Northwestern edge of Aquia formation at overlap, mostly concealed by gravel and sand
- Kmo — Monmouth formation
- Kml — Matawan formation
- Kmgr — Magothy sand and Raritan clay
- Kp — Potomac group *(Largely covered by fine gravel with some alluvium)*
- pC — Granite, gneiss, slate, etc. *(Largely covered by fine gravel with some alluvium)*

Miocene — Eocene — Upper Cretaceous — Lower Cretaceous — Nanjemoy formation — TERTIARY — CRETACEOUS — PRE-CAMBRIAN

BALTIMORE — PATAPSCO RIVER — BACK RIVER — ANNAPOLIS — MAGOTHY RIVER — SEVERN RIVER — CHESAPEAKE BAY — POTOMAC RIVER — PATUXENT RIVER — DISTRICT OF COLUMBIA — ARLINGTON — ALEXANDRIA — Rockville — Towson — Ellicott City — Catonsville — Jonestown — Savage — Laurel — Burtonsville — White Oak — Silver Spring — Tacoma Park — Takoma Park — Brightseat — Largo — Ritchie — Oxeland — Suitland — Anacostia — Silver Hill — Meadows — Camp Springs — Woodyard — Fort Washington — Piscataway — Marshall Hall — Accokeek — East Falls Church — Falls Church — Leeland — Upper Marlboro — Mitchellville — Collington — Rutland — Davidsonville — Birdsville — South River — Mayo — Owensville — Golesville — Sudley — Drury — Findell — Fairhaven — Croom — Friendship — Dunkirk — Chaltenham — Nottingham — White Landing — Millersville — Crownsville — Bowie — Odenton — Gambrills — Bay Ridge — Arundel



GEOLOGIC MAP AND CROSS SECTIONS OF CALVERT FORMATION AND PAMUNKEY GROUP IN MARYLAND AND NORTHERN VIRGINIA



GEOLOGIC MAP AND CROSS SECTIONS OF CALVERT FORMATION AND PAMUNKEY GROUP IN MARYLAND AND NORTHERN VIRGINIA

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 62. PP. 745-780, 9. FIGS., 4 PLS. JULY 1951

STRUCTURAL RELATIONS OF CRETACEOUS AND TERTIARY FORMATIONS IN PART OF MARYLAND AND VIRGINIA

BY NELSON HORATIO DARTON*

ABSTRACT

This paper presents results of study of the structural and overlap relations of several formations of Tertiary age in the region east of Washington, Baltimore, and Fredericksburg. Attention is also given to the relations of various formations of Cretaceous age (Upper and Lower).

The altitude of the base of the Calvert formation (Miocene) was determined at many places, and from these data structure contours were constructed as shown in Plate 1. These show that in a wide area the base of the Calvert has a fairly regular easterly slope of about 10 feet to the mile, with a somewhat steeper rate in the outliers west of Washington. In the Baltimore region this southeasterly slope averages nearly 15 feet to the mile, also with some steepening on the west. In the Fredericksburg region the slope is less than 10 feet to the mile, and farther south this rate carries the plane of Calvert overlap west onto the crystalline rocks.

The Econe succession which I named the Pamunkey formation in 1891 was later divided by W. B. Clark into a lower formation, Aquia, and an upper one, Nanjemoy, the latter having a basal member of clay, named Marlboro. Near Washington this clay member thins out to the west under the Miocene, the edge of which also extends considerably farhter west than the edge of the overlying greensand of the Nanjemoy. The last named gradually thickens to the east and south. South of Fredericksburg the Aquia formation overlaps the edge of the Potomac group slightly, onto the old crystalline rocks, and the Potomac in turn is overlapped by the Calvert formation (Miocene), the Nanjemoy formation with its Marlboro clay member having thinned out or been eroded.

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* Deceased February 28, 1948. Dr. Lloyd W. Stephenson and Dr. C. Wythe Cooke kindly read the manuscript. Doctor Cooke has added some footnotes in regard to more recent work.

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Introduction

This paper presents results of an investigation made in 1936 to 1940 to ascertain the relations of the Upper Cretaceous and Tertiary formations in part of the Coastal Plain. The author's studies in the region were initiated by W J McGee about 50 years ago and resulted in the classification of the formations and the mapping of large areas. Four folios were published by the U. S. Geological Survey, data were supplied for maps by the State surveys of Maryland and Virginia, reports on the geology of the Washington, Baltimore, Fredericksburg, and Richmond regions were issued, and the conditions of underground water supplies from New Jersey to South Carolina were stated. Two late contributions by the present author on the area are a Bulletin of the U. S. Geological Survey (Darton, 1939), a Professional Paper on *Configuration of the bedrock surface in the Washington region*, and a geological map (1947).

The earlier work in Maryland and Virginia established a foundation for the present field investigation which was made with a grant from the Penrose Bequest of The Geological Society of America.

It has long been known that the structural relations and overlaps of the later Cretaceous and Tertiary deposits in these States were somewhat complex, and it was believed that a special study of them would throw light on the events in Cretaceous and Tertiary times. Accordingly the formations have been restudied with special attention to their overlap relations and the precise altitudes of their contacts. The maps, cross sections, and lists of bore holes here presented set forth the principal features and also will afford a basis for further investigation.

The altitudes of contacts were ascertained from exposures and from some 200 holes bored 5 to 35 feet deep, with an auger which brought up samples on its helix. The diameter of the bit is 2 inches, and 3-foot sections of ½-inch iron pipe were used for extensions; a cross bar served at the top, and a wagon jack was used when lifting was difficult. In most cases the altitude was determined by hand leveling to bench marks or to points whose altitudes are shown by contour lines on the maps.

In this region later geologic time is represented in small part by formations, and long time intervals are represented by the unconformities above and below them. Probably in these intervals there was extensive deposition of materials, which later were eroded during uplifts. While the principal uplifting was widespread it varied in amount from place to place, causing tilting and oblique truncation and irregularity of overlaps, notably in members of the Eocene succession and across the western margin of the Upper Cretaceous strata.

Notable variant features in sedimentation in the area are the attenuations of original beds and the overlaps of lower members by higher ones on the sloping shore of a basin. Such relations are difficult to unravel in detail, and important evidence can be secured only by a study of *stages* in the formations as indicated by fossils. There is the further qualification that assemblages of fossils vary with conditions of sedimentation, clearness and depth of water and food, and other controlling factors. Probably a close study of the distribution of diatom assemblages in the Calvert formation will give criteria for the earlier Miocene beds.

Previous Work

The Coastal Plain of Maryland and Virginia was almost a virgin field in 1890 when I was assigned to its study by the U. S. Geological Survey, under W J McGee. Rogers, Conrad, and others had reported Tertiary fossils, and

later Fontaine described the plants of the Potomac group. McGee's *Three formations* (1888) and his report on the geology at the head of Chesapeake Bay (1888) were truly important. My first geologic map of the Washington region was published in 1891, and several other contributions were printed, including a folio of the Washington region (1901). Since then the Maryland Geological Survey published papers and county reports and the Patuxent folio (Shattuck *et al.*, 1907) utilizing much material from earlier publications. Clark and others (1912) studied the Virginia area, parts of which were mapped in my Washington, Fredericksburg, and Nomini folios of the U. S. Geological Survey. A map, by myself, of sedimentary formations in the Washington region was issued in 1947 by the U. S. Geological Survey.

CRETACEOUS

Potomac Group

The general character and relations of the Potomac "formation" in Maryland and Virginia were determined by McGee and the writer, prior to publication of the Fredericksburg folio. The principal relations in the Baltimore region were set forth by the writer in 1892, in the Washington region by Darton and Keith in 1901, and in the Richmond region by the writer in 1911. Water resources and other special economic features were treated in various publications.

The Potomac formation of McGee included at its top several deposits now known to be Upper Cretaceous. In 1893 I separated the uppermost of these as the Magothy formation, and in 1897 Clark and Bibbins separated the next unit below as the Raritan formation. They also subdivided the thick mass of underlying deposits into the Patapsco, Arundel, and Patuxent formations, all separated by unconformities and overlapping to some extent; these comprise the Potomac group.[1] I have not mapped these three formations separately, but the Maryland Survey has done so in county maps and in the Patuxent folio (Shattuck and others, 1907).

[1] The Patuxent formation is still classified as Lower Cretaceous; the Arundel and Patapsco are now classified as Upper Cretaceous. C. W. Cooke

The Potomac group does not represent a large part of Lower Cretaceous time, and there are notable breaks within the group as well as above and below the Raritan and Magothy formations although all five formations have the same general attitude with gentle eastward dip. Bones found in the Arundel formation have Upper Cretaceous affinities according to Gilmore.

Structurally the Potomac group is a wedge-shaped mass lying on the east-sloping floor of crystalline rock, and well records show that it thickens eastward to more than 1000 feet. The rock floor of gneiss and granite is in general remarkably smooth with a regular slope to the east of about 100 feet to the mile near Washington. All obtainable data as to the configuration of the crystalline rock floor in the Washington area are set forth in a report transmitted to the U. S. Geological Survey in 1941 for publication as a Professional Paper, and the configuration about Baltimore is shown on a map issued by the Maryland Survey.

Raritan Formation

The widespread sheet of clay (Raritan formation) below the Magothy and Monmouth formations east of Washington was long regarded as the uppermost member of the Potomac group, but it was traced to New Jersey by the Maryland Geological Survey and in 1897 classed in the Upper Cretaceous by plants identified by Berry. It lies unconformably on the Potomac group and dips gently eastward. Its thickness is 50 feet or less east and south of Washington, most of it is clay, much of it red. It contains some sand, however, both in admixture and in lenslike bodies. Some regard the glass sand on Severn River as lenses in the formation. According to the Maryland Geological Survey the Raritan clay thins out to the south, for at Fort Washington and Glymont it is absent.

Plants collected by Berry from the Raritan clay on the west slope of Good Hope Hill are: *Asplenium dicksoneanum, Salix lesquereuxii, Ficus ovatifolia, Platanus heeri, Aspidiophyllum trilobatum, Protophyllum sternbergii, P. multinerve, Cinnamomum newberryi, Leguminosites canavaloides, Aralia washingtonia, Aliatopsoides*

cretacea, and *Diospyros vera*. Two of these species occur also in the Magothy formation.

Magothy Formation

In 1893 I called attention to a distinct stratigraphic unit in eastern Maryland which had been included in the top of the original Potomac formation. I named the unit "Magothy formation" from extensive exposures on Magothy River. It is overlain by a southern extension of the New Jersey marl succession which I mapped as the "Severn formation" to its termination at Fort Washington a few miles south of Washington.

The Magothy contains an abundant flora (Berry, 1907). Some mollusks, reported from dark sand just east of Anacostia, undoubtedly came from the overlying Monmouth formation for they were marine species characteristic of that formation such as I had collected there long before; typical Magothy sand is well exposed just below it.[2]

The thickness of the Magothy ranges up to 60 feet or more. Its outcrop ends to the south near Anacostia, and it is absent in several places northeast of Washington. In northeastern Maryland it is overlain unconformably by the Matawan formation, but south of the Bowie region where the Matawan thins out it is overlain by the Monmouth formation and, near the northeastern corner of the District of Columbia, by the Calvert formation (Miocene). Doubtless, in these overlap areas, formations from Aquia to Monmouth were deposited but were eroded. Possibly, also, the Magothy was not deposited continuously over the entire Coastal Plain area, especially near the western edge along the present outcrop zone east of Washington. It evidently was a beach-and-stream deposit, and its surface was eroded somewhat before overlapping strata were deposited. Possibly there was a small amount of differential uplift or tilting; unfortunately no data on this were secured.

Late Upper Cretaceous Unconformity

A considerable interval separated the deposition of the Raritan and Magothy formations and also the deposition of the Magothy and the southern extension of the New Jersey marl series. In these intervals beds may have been deposited and since removed, and locally there was deep truncation of the edges of preceding clays and sands down to and below the base of the Potomac. This planation increased in amount in Virginia where the total uplift was greater and only the lowest part of the Potomac group remains at the outcrops.

The Raritan clay and Magothy sand were deposited in wide areas in Maryland and northward, but their original extent cannot be surmised, for after deposition of each one there was uplift in which in central-eastern Maryland considerable of the deposit was removed. The New Jersey marl series was then laid down in a marine submergence of wide extent and long duration, but the limits of its original deposition to the south and west are not known. The ending of the outcrop of the Matawan formation near Bowie, Maryland, is due to thinning out and overlap by the Monmouth formation which thence outcrops continuously south to the bluff at Fort Washington where it lies between the Aquia formation (Eocene) and the lower formation of the Potomac group.

These relations indicate oscillations of submergence and diagonal truncations which have caused variations in the stratigraphic column left in various areas, at least those now represented by outcrops. How much of the variations are due to diminution of volume of deposits in the original area of deposition and slope of shore, or to truncation of beds by erosion can be determined only by study of the faunal relations at overlaps. Undoubtedly also there was considerable tilting or differential uplift between the planations. In general, uplift and erosion increased to the south, for the outcrops of Magothy sand and Raritan clay cease a short distance south of the latitude of Washington, and the Monmouth outcrop extends only a few miles farther south, for in Virginia deposits of Eocene and Miocene age extend directly across lower Potomac beds and overlap onto the crystalline rocks.

Matawan Formation

The lowest member of the New Jersey marl series outcrops from near Bowie northeastward in the Coastal Plain of Maryland, but it thins

[2] The mollusks referred to are Miocene. No Magothy fossils are known from Maryland, and the formation was not recognized in Prince Georges County or the District of Columbia when resurveyed in 1948. C. W. Cooke

out at the outcrop south of Latitude 39°, a short distance south of Bowie. To the north it appears below the Monmouth formation, which also dips gently southeast, and, although they of the Matawan formation passes below sea level. The maximum thickness exposed is 40 feet. The formation thins out a short distance south of Bowie, a feature not shown on previous

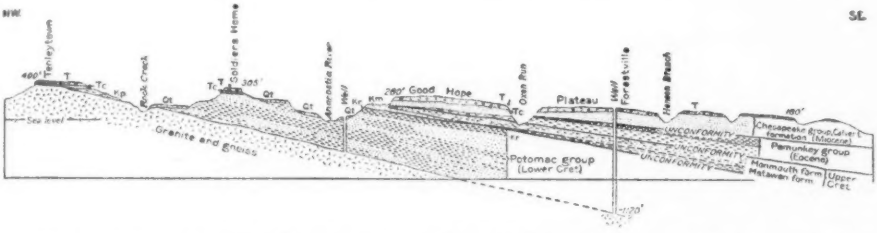

FIGURE 1.—SECTION THROUGH WASHINGTON AND EASTWARD THROUGH PART OF THE COASTAL PLAIN
Showing the succession and relations of the sedimentary formations. Qt, Terrace gravel and loam (Quaternary); T, gravel of plateau (Pliocene?); Tc, Calvert formation of Chesapeake group (Miocene); Km, Magothy formation, underlain in part by Kr, Raritan formation (Upper Cretaceous); Kp, Potomac group (Lower Cretaceous).

TABLE 1.—HOLES IN MATAWAN FORMATION IN AND NEAR ANNE ARUNDEL COUNTY, MARYLAND

Location	Altitude of ground	Depth of hole	Altitude of base of Matawan	Remarks
Conaway, ½ mile west	190	14	176	To hard bed, probably Magothy
Conaway, ½ mile southeast	92	23	below 69	Not to bottom of formation.
Patuxent Station, 2 miles east	220	3	below 217	Not to bottom of formation.
Patuxent Station, 2½ miles east by south	205	11	below 194	Not to bottom of formation.
Odenton, 1½ miles southeast	205	20	185	To sandstone (Magothy).
Millersville, 1 mile south	98	8	84	To coarse gray sandstone (Magothy).
Millersville, 2 miles southeast	80	32	below 48	Nearly to bottom of formation.
Chesterfield, 1 mile northwest	55	28½	near 26	Nearly to bottom of formation.
Chesterfield, ½ mile east, near creek	19	19	sea level	To hard bed (age?)
Crownsville, 2 miles northeast	47	7	40	To sand (Magothy).
Burns Crossing, 1½ miles north-northeast	197	7	190	To sand (probable Magothy).
Collington, 2½ miles northeast	100	3	97	To coarse sand (Magothy).

are separated by unconformity, the materials are so much alike and fossils so infrequent that in places it is difficult to distinguish them.

The basal contact of the dark marly Matawan sand on the sand or sandstone of the Magothy formation, however, is plain everywhere in the outcrop zone northeast of Bowie. One good exposure of contact is in the railroad cut about 350 yards west of Millersville at an altitude of 125 feet; others are three quarters of a mile south of Waterbury at 80 feet above sea level, at Benfield at 120 feet, and on Round Bay below Whites Landing where the base detailed maps. I have not, however, mapped its margin precisely in that vicinity.

Monmouth Formation

Prince Georges County and District of Columbia.—In its southern extension across Prince Georges County the Monmouth formation was for many years mapped as Matawan. It was so represented in the Washington (Darton and Keith, 1901) and the Patuxent (Shattuck *et al.*, 1907) folios and on the geologic map of the Prince Georges county by Miller *et al.* (1911);

the State geological map (1933) shows the Monmouth outcrop ending not far south of Bowie. However, the outcrop of the Matawan formation ends a short distance south of Bowie, and the outcrop of the overlapping Monmouth

tions near Washington issued by U. S. Geological Survey, October 1947.

The Monmouth formation is dark sand or marl with considerable mica in small scattered flakes. Near Bowie and northeastward it lies

TABLE 2.—HOLES BORED TO BASE OF THE MONMOUTH FORMATION IN PRINCE GEORGES COUNTY AND THE DISTRICT OF COLUMBIA

Location	Altitude of ground	Depth of hole	Altitude base of Monmouth	Remarks
Brightseat, 2 miles east of Bald Hill Branch	100	15	91	Sand (Monmouth) 0–9 feet, lead, brown, and red clays (Raritan) 9–15 feet.
Suitland road, few rods east of D. C. stone No. 3	205	32	175	Black marl (Monmouth) 18–30 feet, Reddish clay (Raritan) 30–32 feet.
Congress Heights, 1¼ miles southeast, south of Wheeler Road	160	6	154	To hard bed (Magothy).
Congress Heights, 1½ miles east-southeast, on Wheeler Road	181	16	—	Not quite to base of formation.
Massachusetts Avenue, extended	195	7½	188½	Calvert 0–6 feet, black sand (Monmouth) 6–6½ feet, gray clay (Raritan) 6½–7½ feet.
Hartford Street, near 22nd	193½	6½	187	To hard bed (Magothy).
Branch Avenue, just east of Oxon Run	170	9	166½	Clay (Raritan) 3½–9 feet.
Oxon Hill postoffice (Gilman Corner) 1¼ miles southeast (just east of B.M. 81 feet)	85	14	71	Light-gray clay (Raritan probably) at 14 feet.
Friendly, ¼ mile west by north in creek	55	10½	45	Light-gray clay (Raritan probably) at 10½ feet.

extends to the bluff at Fort Washington. I collected fossils from it (Severn formation) at the latter place in 1892 on the suggestion of Uhler. Soon afterward, however, it was classed by W. B. Clark as Matawan of the New Jersey succession, an error which was not rectified until the Upper Cretaceous volume of the Maryland Survey appeared (Clark and others, 1916), when the Matawan outcrop was mapped as ending near Bowie, and long lists of Monmouth fossils from various localities south of that place were presented. These fossils were identified, described, and correlated with the Monmouth by Dr. Julia A. Gardner. The outcrop just east of Washington is correctly shown on the map of the Sedimentary Formation on the Matawan formation, but farther south it overlaps onto the Magothy formation and at Fort Washington it lies on the lower formation of the Potomac group. The Monmouth beds are richly fossiliferous in places, notably near Seat Pleasant, Brightseat, and on the creek a mile west of Friendly where hard layers contain many shells and impressions of an abundant and characteristic Monmouth fauna.

A few fossils characteristic of the Monmouth are: Pelecypoda—*Leda rostratruncata*, *Exogyra costata*, *Crenella serica*, *Liopistha protexta*, *Aphrodina protexta*, and *Pholas pectorosa;* Gastropoda—*Pyrifusus monmouthensis* and *Morea marylandica;* the ammonite genus *Sphenodiscus*. The list of those from near Brightseat and

Friendly comprises more than 150 species, many of them characteristic of the formation.

The Monmouth formation, 40 feet thick in most of Prince Georges County, thins to the south and west, especially in Good Hope Hill where the Eocene also has been removed by Miocene erosion. In one place on the northwestern slope of Good Hope Hill it is only 3 feet thick and lies directly on Magothy sand or Raritan clay. In places it thins out entirely.[3] Much if not all of this thinning is due to erosional truncation, partly late Cretaceous or Eocene and partly post-Eocene. It is not easy to recognize the Monmouth-Aquia contact without close scrutiny for fossils. The overlap by the Calvert formation in Good Hope Hill (Pl. 2, fig. 1) is very distinct. It is a nearly smooth plain with sharp contrast in materials at 220 feet above sea level, lying on Magothy gray sand; but in places it lies on Raritan clay with strong unconformity. In the Capitol Heights and Seat Pleasant regions the Monmouth formation is conspicuous in road cuts. To the southeast it is overlain by Aquia marl and is 25 feet or more thick.

One of the finest exposures up to 1938 was in the cut of the abandoned Chesapeake Beach Railroad just north of Central Avenue, where black Monmouth sand lies on light-gray Raritan clay near the level of the tracks, at an altitude of 143½ feet. Here and just east the formation is highly fossiliferous. The basal contact is exposed along Central Avenue in the summit about a quarter of a mile west of the Chesapeake Beach Railroad bridge, at an altitude of 157 feet. Near Brightseat the contact is exposed on the west side of Bald Hill Branch, 27 feet above the creek, at an altitude of 112 feet.

In the northeastern corner of the District of Columbia the Monmouth formation lies mostly on sand and sandstone of the Magothy formation, but in places it overlaps on Raritan pink clay, and it thins out locally. On Southern Avenue, 400 feet north of Central Avenue, it is 20 feet thick with its base at an altitude of 185 feet, on red variegated clay (Raritan). On Massachusetts Avenue near the District line the altitude of the base is 188 feet. At the corner of Drake Place and 54 Street the Monmouth is 17 feet thick, and the basal contact is at an altitude of 203 feet. It is slightly higher in an outlier just north of Drake Place a few yards east of 51 Street.

The Monmouth basal contact extends into the District of Columbia at H Street near 53 Street where a 7-foot hole by the road reached white clay (Raritan) at an altitude of about 193 feet. On the high hill on the south side of Pennsylvania Avenue near 32 Street it is 3½ feet thick and lies on Raritan clay at 207 feet above sea level. On Hillcrest Road northwest of W Street the altitude of the contact is 185 feet. On the Good Hope Road northwest of Good Hope the formation lies between Magothy gray sand at 216 feet above sea level and Calvert sandy clay at 220½ feet (Fig. 2), and in a gully three quarters of a mile northeast of Good Hope (cross roads) 4 feet of Monmouth black sand lies on Magothy sand at an altitude of 190 feet. On a farm road two fifths of a mile southwest of Garfield School it appears to lie on Magothy brown sandstone at about 175 feet altitude. On Walker Road 300 feet west of District of Columbia boundary monument No. 4 the road cut exposes the contact on Magothy sand at 177 feet. In the very fine exposure at the Orloff sand pit (1940) the outcrop of black Monmouth sand 5 to 6 feet thick extends across the quarry face between the Calvert gray clay and the Magothy white sand, with base at 196 feet (Fig. 3).

On the creek 1½ miles west of Silver Hill the Monmouth formation lies on Raritan pink clay at an altitude of 157 feet. It is exposed or reached by holes, at several places west and southwest of Silver Hill, especially on the slopes of Barnaby Creek where it overlaps the eastern edge of Magothy sandstone which thins out south of Anacostia. It is 5 feet thick (altitude 113–118 feet) in a gully north of the road half a mile northeast of Fort Foote, 10 feet thick (127–137 feet) on the main road a quarter of a mile west of Gilman Corner (old Oxon Hill village), and 3 feet thick (127–130 feet) in a gully half a mile to the west. In gullies half a mile south of New Glatz where the Magothy is absent, and also in fine exposures in gullies on the east side of the main road half a mile northeast of New Glatz (altitude 86 feet), weathered Monmouth sand lies on the irregularly eroded surface of the Raritan clay.

[3] The Monmouth is probably completely overlapped by the Miocene in Good Hope Hill. C. W Cooke

Along the creek west by north of Friendly the Monmouth formation contains hard limy ledges crowded with fossils. A 10½-foot hole bored here reached light-gray clay supposed to be Raritan, at an altitude of 45 feet. Not far above this outcrop, the stream cuts into

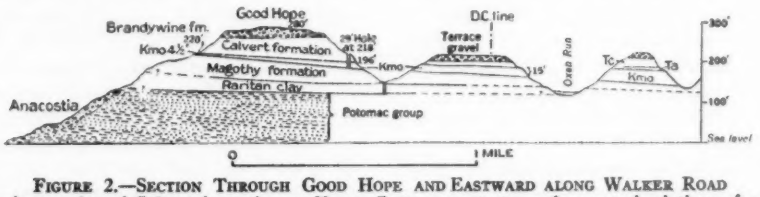

FIGURE 2.—SECTION THROUGH GOOD HOPE AND EASTWARD ALONG WALKER ROAD
Showing overlap of Calvert formation on Upper Cretaceous strata, and supposed relations of western margin of the Aquia formation.

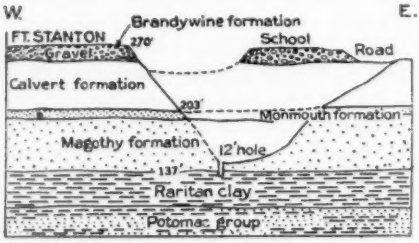

FIGURE 3.—SECTION AT ORLOFF SAND PIT IN THE SOUTHEASTERN PORTION OF ANACOSTIA, D. C.
Looking east.

Aquia marl which carries abundant Eocene fossils. At Fort Washington bluff on Potomac River about 4 miles farther southwest, the dark micaceous sand (Monmouth) lies on Potomac sandy clay at an altitude of 55 feet; and it is overlain unconformably by the Aquia formation.

Throughout this area the base of the formation slopes east at an average rate of 40 feet to the mile, or slightly greater than that of the Aquia contact at its top, so that it thickens to the east or southeast. Whether this thickness indicates increased deposition or the presence of higher members, or only increased truncation to the west has not been determined.

EOCENE

Pamunkey Group

General statement.—In my earliest description of the Eocene strata east of Washington and in Virginia, I designated them Pamunkey formation (Darton, 1891a), and they were mapped as a unit under that name in the Washington geologic sheets (Darton, 1891b; Darton and Keith, 1901). In 1896 Clark divided the formation into stages, and in 1901 he split it into two formations, the Aquia and the Nanjemoy. Owing to overlaps and possibly in part to thinning, the sequence of beds varies. Both formations thin out to the west, especially in Maryland where the Calvert formation (Miocene) overlaps all the Eocene strata and also the Monmouth and lower formations.

In a wide belt in the Coastal Plain of Maryland and Virginia, Pamunkey group is exposed in the valleys of the Potomac, Rappahannock, James, and other rivers. During at least part of Eocene time the sea submerged the entire Coastal Plain province, but the location of the original western limit or the old Eocene shore lines, and also the original thickness of deposits, cannot be known, because there has been considerably more uplift to the west and consequently greater truncation in that direction. The present investigation with drill holes has yielded many new facts as to the overlap relations along the western margins of both formations, especially where they are overlapped by the Calvert formation.

Aquia formation.—The Aquia formation underlies most of tidewater Maryland and Virginia, with thickness of possibly 150 feet to the east. Owing to the low dip the outcrop zone is moderately wide at most places, especially in the larger valleys. To the north the formation lies unconformably on the Monmouth formation and to the south on the Potomac group, and in Virginia its margin finally overlaps west onto the old crystalline rocks. Clark and others (1912) divided the formation into several stages with characteristic fossil assemblages, but in

the present investigation these stages have not been considered. In most of the area the Aquia formation is overlain unconformably by the Nanjemoy formation, and to the west the Calvert formation extends across the upturned edge of the entire formation.

In Anne Arundel County there are extensive exposures along the valleys of Severn, South, and Patuxent rivers, mostly of weathered material; the outcrop extends down the last-named valley to a point near Latitude 38° 50′ where the top of the formation passes below sea level.

The Aquia formation is bared in a wide zone in the valleys of Southwest, Western, and Collington branches in Prince Georges County. It rises gently to the northwest. Its base is at an altitude of 150 feet in an exposure 1½ miles east of Ardmore, on a rise which brings into view the underlying Monmouth formation so that it is exposed in the deeper valleys for a few miles. The uppermost beds of Aquia greensand marl with highly fossiliferous hard layers outcrop a few feet above sea level at Marlboro where the total thickness of the formation is about 100 feet. These beds are overlain by the Marlboro pink clay member at the base of the Nanjemoy formation, a feature which continues up the valley of Charles Branch and north up the valley of Western Branch to near Latitude 38° 51′, beyond which the Aquia formation is overlain directly by the Calvert formation; the Nanjemoy formation is absent. There are extensive outcrops about Ritchie and to the southwest under the high plateau, and beyond the District of Columbia line. The greensand marl is exposed at many places in the slopes of Henson Creek, but the bottom of the Aquia formation was not reached in a 36½-foot hole (to altitude 120 feet) on this creek at a point 2½ miles due west of Camp Springs. Its thin edge is exposed west of Suitland and in a new (1936) road cut on Branch Avenue just east of Oxon Run a short distance east of the District line where it is about 6 feet thick and lies on the Monmouth formation at an altitude of about 198 feet. Many distinctive fossils are present. It is well exposed in the creek a short distance west of Friendly and in the bluff at Fort Washington; it lies on the Monmouth formation at both places. Bagg (1898) reported in the Aquia formation of Maryland two fossils characteristic of the Rancocas marl of New Jersey (formerly regarded as upper Cretaceous) which he believed lived on into Eocene time; they are *Terebratula harlani* and *Gryphaea dissimilaris*. The former, found by Stephenson (in 1937) to be associated with *Kummelia americana*, occurs with characteristic Aquia fossils in a road cut three quarters of a mile west of Oak Grove, or 2.6 miles west of Leeland on the Popes Creek Branch, Pennsylvania Railroad, in Prince Georges County. The *Terebratula* occurs in a vertical range of 5 feet, in part in hard masses. The shells are large and thick, and evidently in place. Monmouth marl outcrops 20 feet below. *Gryphaea dissimilaris* was found near Clifton Beach (Potomac River) in a bank of highly fossiliferous Aquia marl.

The Aquia formation underlies all of Charles County except where the wide valley of Potomac River has trenched into the underlying Potomac group. A wide area has been bared by erosion in the valleys, but in them the Aquia is now mostly thickly overlain by alluvium and terrace deposits. To the east the Aquia passes beneath the Nanjemoy and Calvert formations on a plane of unconformity sloping gently east-southeast. There is an extensive exposure in the Potomac River bank at Glymont, and others occur at intervals along the river from Mallows Bay to a short distance below Clifton Beach. The long exposure near Glymont is of the Piscataway stage of the Aquia formation, about 50 feet thick, lying on a nearly smooth, apparently level surface of variegated clay of the Potomac group. The contact is about 20 feet above sea level, and about 8 feet above the base is a 20-foot bed of greensand marl somewhat weathered, containing many fossil shells (Zone 2 of Clark and Martin). A hole, 14 feet deep, a quarter of a mile southeast of Chapman Point at 70 feet above sea level, is all in Aquia marl.

Nanjemoy formation.—The upper formation of the Pamunkey group was separated by Clark and others (1901), with type locality in the neighborhood of old Nanjemoy post office in Charles County, Maryland. It is a thick body of greensand divided into stages and an underlying widespread basal sheet of clay averaging 20 feet thick, called the Marlboro clay member.

The extent, stratigraphic limits, and overlap relations of this member have not been described, and, as these present overlap features that throw much light on the history, I have given special attention to them. I now believe that this Marlboro clay should have been separated as a formation.

The Nanjemoy formation underlies the higher plateau areas of central and southern Anne Arundel, Prince Georges, and Charles counties. It is deeply incised by the valleys of the South, Patuxent, and Potomac rivers and branches. It dips southeast. The base is at sea level near the mouth of South River, and its top passes under it on Chesapeake Bay not far north of Fairhaven, under Patuxent River near White Landing, and under Potomac River a few miles below Popes Creek.

The Nanjemoy formation thins out or is bevelled off to the west, and its margin in that direction is overlapped by the Calvert clay which from there west lies on Aquia and lower formation. The relations are visible in outcrops and road cuts, or revealed by bore holes.

The unconformity between the Nanjemoy and Calvert formations is an erosion plane representing a long part of mid-Tertiary time. It resulted from uplift with local irregularities in amount, in general increasing to the west, and with widespread planation.

The Marlboro clay member at the base of the Nanjemoy formation outcrops across Anne Arundel, eastern Prince Georges, and Charles counties, and far south across the Coastal Plain of Virginia. It lies unconformably on the glauconitic sand or marl of the Aquia formation. Its thickness at most places is near 20 feet, but it thickens and thins irregularly. The material is pure clay, mostly pink, not "argillaceous sand"; some of it is gray. At its western edge it thins out in a short distance, and for many miles the Calvert beds extend west across it onto Cretaceous strata.

There are extensive outcrops near Marlboro, and it is exposed in many places in slopes south of South River from the vicinity of Davidsonville down the valley of Patuxent River to Lyons Creek, also in southwestern Prince Georges County, and in Charles County. Outcrops are mostly in road cuts; but, as these are rather rare, many holes had to be bored to ascertain its thickness and position.

The portion of the Nanjemoy formation that overlies the Marlboro clay member is mostly a dark "greensand" containing glauconite. It is 100 feet or more thick to the east but thins out in a short distance near its northern and western margins. Clark (1912) divided it into stages, each characterized by assemblages of fossils. I did not study these stages but traced the thinning of the northern and western edges to ascertain the relations of the overlap by the Calvert formation. This overlap shows beveling or truncation due to uplift in Eocene or early Miocene time, an interesting episode in geologic history. The greensand portion of the formation thins out to the west a short distance east of the zone in which the Marlboro clay member thins out. The relations are shown by scattered outcrops, and many additional altitudes of contacts were determined by bore holes.

The outcrop of the Nanjemoy greensand extends across Anne Arundel, Calvert, Prince Georges, and Charles counties in a northeast-southwest direction. Exposures are found where the overlying Calvert clay has been eroded; they extend far east and south in the valleys, and north and west on the ridges and plateau remnants. The greensand is widely covered by hillside wash and in the larger valleys by alluvium. Where the Nanjemoy greensand is thick, its upper limit has been determined from outcrops and bore holes, but where the underlying Marlboro clay could be reached its lower limit and total thickness were ascertained by holes.

The northernmost remnant areas of the Nanjemoy are small outliers of pink clay (Marlboro member) on the ridge between Severn and Patuxent rivers near Latitude 39° 31′, and one of about 200 acres capping the ridge just north of South River, west of Broad Creek. South of South River the clay is continuous in a large area, but Patuxent River trenches it widely to near White Landing, and on Chesapeake Bay its top goes below sea level near Latitude 38° 47′, under a cover of low-level terrace deposit. The basal Monmouth clay, mostly pink, underlies much of the high plateau, with a thickness of 20 to 25 feet, and the overlying greensand, which attains a thickness of 80 feet or more to the south, thins out north of Latitude 38° 55′ a short distance south of the northern edge of the Marlboro clay member.

A notable outcrop of the latter is in cuts and in an excavation near the road forks where the road to old South River post office leaves the Mayo road. This is at a store a quarter of a mile east of Glebe Creek and 3 miles northwest of Mayo. The section about here shows Calvert sands with a basal contact at 57 feet above sea level, on 27 feet of greensand (upper Nanjemoy), underlain by 20 feet of pink clay (Marlboro member) which is cut through by Glebe Creek at the road crossing a short distance west. A fine bluff of Marlboro clay on the southeast bank of this creek a mile north-northeast of the store shows its contact on the Aquia formation at an altitude of 30 feet.

The glauconitic sand of the Nanjemoy formation is 35 feet thick just west of Contee's Wharf and may be 70 feet thick where the road to the south crosses Muddy Creek (2 miles southeast of Birdsville). The Marlboro clay makes a bluff at sea level on the west side of Big Island in Rhodes River and at Murray's Wharf, but it could not be traced northeast of this area owing to the cover of terrace deposit. Dutchmans Point shows a bank of greensand, doubtless the upper Nanjemoy, and this member appears in the wave-cut bank at Thomas Point. A hole bored 23 feet at the foot of the 4-foot bank of weathered greensand just east of Marshy Point did not reach the clay, and I was unable to find it rising on the dip along the bay shore at Arundel-on-the-Bay and Bay Ridge, owing to a cover of terrace deposits. Possibly, also, the clay thins out in this vicinity. The clay and the overlying wedge of greensand are exposed at many points east, west, and north of Davidsonville, and both were reached in several holes bored to ascertain the relations.

Near Rutland several road cuts expose the basal contact of the pink clay. One, 2 miles east of Rutland, is at an altitude of about 100 feet, and another, 2¼ miles southeast, is at 113 feet. About Davidsonville there are several exposures of it. One, 2½ miles south by west of the village, is at an altitude of 35 feet; another, 1 mile east, shows a contact in which the clay, extending from an altitude of 95 to 70 feet, is overlain by 5 feet of greensand. In a cut 1.6 miles north-northeast of Davidsonville where the greensand is absent, the Marlboro-Calvert contact is at an altitude of 140 feet, and the pink clay was bored into 11 feet, but bottom was not reached. A mile northeast of Davidsonville the pink clay is overlain by greensand at an altitude of 133 feet, and an 11-foot hole at the contact was in clay. The clay is exposed in the creek bank 2½ miles south by west of Davidsonville at an altitude of 35 feet.

In cuts 2½ miles northeast of Birdsville post office the clay outcrops at an altitude of 40 to 20 feet. Near old South River post office it is overlain by greensand at an altitude of 35 feet, and on the east side of Glebe Creek its base on Aquia greensand marl is about 15 feet above sea level.

In a road cut 1¼ miles northwest of Bayard, the top of the clay is at an altitude of 42 feet, and it is also exposed on stream banks for a short distance.

On the ridge between Patuxent River and Chesapeake Bay the northern edge of the greensand of the Nanjemoy formation is a short distance north of Davidsonville. It is 2 feet thick in the road cut 1 mile northwest of Davidsonville (altitude 133–135 feet) and 5 feet thick a mile east of that village (altitude 95–100 feet). It thickens to 35 feet just west of Contee's Wharf, and apparently its top passes below sea level not far east of Nutwell. The greensand is exposed at many places on both sides of the valley of Patuxent River from points east of Hall's Station past Marlboro, Hills Bridge, Bristol, and Croom. It is 55 feet thick just west of Hills Bridge and about 40 feet thick near the mouth of Lyons Creek. In the old quarries for diatomite at Lyons Creek Wharf are fine exposures of the basal Calvert contact on Nanjemoy greensand 40 feet above sea level, and the upper part is well exposed under Calvert in cut banks at the "silica" quarry in the east bank of Patuxent River a short distance below Nottingham where the contact is 15 feet above sea level. The top passes below sea level, under alluvium, just above White Landing on Patuxent River. Wells at Chesapeake Beach report clay, some of it pink, at 122–165 feet under 62 feet of gray sand; this indicates Nanjemoy beds from 60 to 165 feet.

The pink clay (Marlboro member) is exposed at several places in Prince Georges County and was penetrated by bore holes near Piscataway. It is exposed in a road cut at an

altitude of about 110 feet at a point 2 miles north of the village, and at from 110 to 103 feet on the road nearly half a mile farther north. It also outcrops at an altitude of 40 to 80 feet on the main road a mile west by north of Piscataway; the lower part not far above a ledge of limestone in the Aquia formation con-

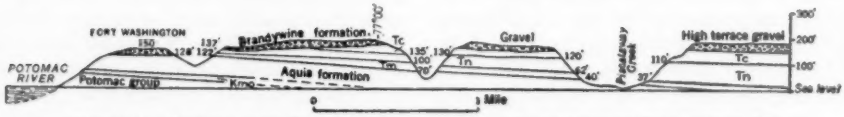

FIGURE 4.—SECTION FROM FORT WASHINGTON RIDGE EAST THROUGH PISCATAWAY, MD.
Showing altitudes of contacts, and the overlap relations of Tertiary and Cretaceous formations.

tains many *Turritellas*. The clay is exposed about 40 feet above sea level on the north bank of Piscataway Creek 1¼ miles east by north of Piscataway where a hole 17½ feet deep did not reach its base. It outcrops in the road cut a few rods east of the Fort Washington gate, where its base is at 122 feet altitude on Aquia formation, and it is cut by the creek just south of the road about 2 miles east of Fort Washington. A hole at this place penetrated pink clay from an altitude of 97 to 70 feet. It outcrops near an altitude of 115 feet in a gully 1 mile south-southwest of Farmington Landing and extends from 82 to 59 feet above sea level in a hole bored on the road half a mile south of that landing. Northwest of Accokeek the clay is absent (Fig. 4).

The Nanjemoy greensand is 40 feet thick at Marlboro and 50 feet thick just north of Croom Station. It thins to 25 feet 3 miles northwest of Marlboro and 3 miles west-northwest of that place and disappears at points not far east of Foxden Hill (2½ miles south-southwest of Leeland). About 3 miles east of Ritchie its western edge lies considerably east of the western edge of the Marlboro clay.

The relations of the formation could not be determined about Meadows and southwestward under the wide plateau where there is a cover of younger formations. On Tinkers Creek at Latitude 38° 48′, the Calvert appears to lie on the Marlboro clay, as it does near Friendly. Two miles farther south, however, the intervening greensand of the Nanjemoy formation is more than 25 feet thick, and on the south side of Piscataway Creek east and south of Piscataway it averages 70 feet, thickening rapidly from the north. Doubtless this thickening continues under the plateau to the south. The top was reached by a 27-foot hole in the bottom of Mattawoman Creek 3½ miles south of Piscataway. It outcrops extensively in the Piscataway Valley which near Piscataway cuts into the underlying pink clay (Marlboro). The greensand thins to the north for it is 25 feet thick in a small valley 2 miles west of the town, where it lies on the pink clay it is near an altitude of 100 feet. Just south of Farmington Landing the thickness is 24 feet with base at an altitude of 82 feet.

Near Accokeek and southward the western edge of the greensand is not revealed, but in a hole a mile southwest of Bryans Cross Road it is 14 feet thick with top at an altitude of 98 feet, while on the road a short distance southwest of Mason Springs it is 34 feet thick with top at 80 feet. Two feet of greensand is exposed overlying the Marlboro clay just north of Rison, but here the surface has been eroded, and terrace gravels deposited. It was reached by a hole 7 feet deep, 2 miles east of Accokeek (altitude of contact 118 feet) and at 86 feet in a 4-foot hole 2½ miles southeast of Accokeek. The Calvert basal contact is exposed at an altitude of 121 feet in road cuts 1 mile southeast of Bryans Road and at 119 feet on the opposite side of the valley. A 22-foot hole bored at this place indicated a thickness exceeding 44 feet. An upper contact is exposed in the road cut a mile northwest of Pomfret at an altitude of 123 feet and in a cut a mile southeast of Pomonkey at 120 feet. In the road cut 2 miles south of Pomonkey where the Calvert contact is 119 feet above sea level, the greensand of the Nanjemoy appears to be 85 feet thick.

The Nanjemoy formation underlies Charles County excepting the narrow area near the Potomac River from which, if it ever was deposited, it has been eroded. The Marlboro

clay member is extensively developed in this county with an average thickness of 20 feet. Near Rison, however, it is only 4 feet thick, expose the clay, pink below, gray above, lying on greensand marl of the Aquia formation and overlain by greensand of the wedge-shaped

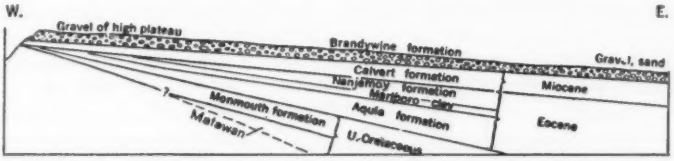

FIGURE 5.—GENERAL RELATIONS OF THE NANJEMOY FORMATION IN CENTRAL-EASTERN MARYLAND

TABLE 3.—HOLES BORED IN MARLBORO CLAY MEMBER IN ANNE ARUNDEL COUNTY, MARYLAND

Location	Altitude of ground	Depth of hole	Altitude of top of clay	Remarks
Governors Bridge, 2 miles east by south	126	3	124	Calvert formation 0–2 feet; pink clay 2–3 feet.
Rutland, 1¼ miles southeast	150	6	144	Calvert formation 0–6 feet to pink clay
Rutland, 1⅝ miles south by east	147	19	129	Calvert formation 0–18 feet to pink clay 18–19 feet.
Davidsonville, 1 mile northwest	130	11	133	Marlboro pink clay 0–11 feet (Hole begins 3 feet below Calvert contact).
Davidsonville, 1½ miles west-southwest on highway (1¼ miles east of bridge)	130	21	118	Greensand 0–12 feet; pink clay (Marlboro) 12–21 feet.
Davidsonville, 2 miles northwest	140	24	120	Clayey gray sand 0–20 feet, clay gray pinkish (Marlboro) 20–24 feet.
South River (old post office) 1 mile north, on road	40	17½	25	Greensand 0–15 feet, clay gray or pink (Marlboro) 15–17 feet.
Birdsville, 2 miles southeast	25	16	9½	Greensand 0–15½ feet, pinkish clay (Marlboro) 15½–16 feet.

and in a hole 1½ miles north of Bryans Road it is 13 feet thick. Much of the clay is pink, but in places it is wholly or in part lead gray. It is very compact or tough and rather different in aspect from clay of other formations.

Data regarding the Marlboro clay in Charles County were obtained from the few outcrops and by several bore holes (Table 3). On the road a mile northeast of Mason Springs the base of the clay member is about 58 feet above sea level. Gullies on both sides of the main road a third of a mile southwest of Mason Springs mass of the upper members of the formation. The base here is nearly 60 feet above sea level, and the Marlboro clay may be 15 feet thick or more, but the top relations are not clearly exposed.

The Marlboro clay exposed on the road a quarter of a mile north of Rison is 4 feet thick and lies on marl of the Aquia formation of undetermined thickness. It is overlain by 2 feet of greensand containing Nanjemoy fossils, and also by terrace gravel, which shows that the surface here was eroded in Pleistocene time.

On the east-west road a quarter of a mile southeast of Doncaster the cut through Stretchmark Hill has walls 10 feet high, of pinkish clay which appears to be Marlboro, and a hole here 17½ feet deep to an altitude of 134 feet failed to reach its base. Possibly, however, the material here is Calvert or even younger. Clay outcropping near the road crossing 2 miles east, at an altitude of 135 feet, was bored to a depth of 12 feet. The very distinctive pink clay was found in several shallow holes bored north of Ironsides and west of Hillside. East of the latter place it is some distance below sea level as the greensand wedge of the upper part of the Nanjemoy dips down and it also thickens greatly in the Port Tobacco region. The location of the western margin of the Nanjemoy strata south of Rison could not be determined owing to cover. In the basin of Nanjemoy Creek in the southern part of Charles County, the type locality of the formation, there are but few outcrops, and these are in the slopes of creeks that have other names than Nanjemoy. Fossils are so few that division into stages is not practicable in this vicinity.

Two and a half miles southeast of Mason Springs the top of the Nanjemoy formation is 116 feet above sea level, and its greensand is about 85 feet thick. Just west of Mason Springs the greensand is about 34 feet thick, but here the surface has been eroded in Pleistocene time. There is a good exposure of the contact with the overlying Calvert in the road cut 1¼ miles southwest of La Plata at 73 feet above sea level. The formation may be bared of Calvert in the bottom of the valley of Zekiah Swamp, but this valley is covered thickly with alluvium. Borings and outcrops a short distance west of Hilltop show the greensand about 85 feet thick (altitude 105–20 feet), and probably it is the same or thicker a mile east of Hilltop and just east of Welcome. The greensand crops out in the ridge north of Trappe Bridge, but its limits are not revealed in outcrops or bore holes. It thins from 85 feet at about 3 miles east of Bryans road to 14 feet in a hole a mile west of the latter place and to zero 1¼ miles north of Bryans Road.

The valley of Port Tobacco River cuts deeply into greensand of the Nanjemoy formation

TABLE 4.—HOLES BORED IN MARLBORO CLAY IN CHARLES COUNTY, MARYLAND

Location	Altitude of ground	Depth of hole	Altitude top of clay	Remarks
Bryans Road, 1¾ miles west-southwest	116	17½	99	Clay 0–3 feet (Calvert), greensand 3–7 feet (Nanjemoy), Clay, pink, 17–17½ feet.
Bryans Road, 1¼ miles west-southwest	98	14	98	Clay, gray and pink 0–14 feet, to greensand marl (Aquia).
Mason Springs, ¼ mile southwest	67	8	—	Pink clay, 0–7 feet, marl (Aquia) 7–8 feet.
Pomonkey, 2 miles south by west on road	50	22	30	Greensand, 0–20 feet, clay (Marlboro) 20–22 feet.
Port Tobacco, 2 miles north by west	63	32	—	Greensand, 0–32 feet, clay not reached.
Ironsides, 1¼ miles north	70	15	57½	Greensand, 0–12½ feet, clay 12½–15 feet.
Ironsides, 1¾ miles northeast	40	16	25	Greensand, 0–15 feet, clay 15–16 feet.
Ironsides, 1½ miles east-southeast	25	12	20	Greensand, 0–5 feet, clay 5–12 feet.
Stretchmark Hill, south of Doncaster (cut)	150	17½	—	All in pink and buff clay presumably Calvert, but may be Marlboro member

which outcrops at a few points in the slopes of the valley and in side valleys and gullies; its thickness is probably 100 feet. Its top was reached by several bore holes (Table 7). A road cut half a mile northwest of Port Tobacco shows Calvert clay lying on the greensand at 68 feet above sea level; the latter outcrops on both sides of the Port Tobacco valley south of this place. High bluffs along the river above and below the mouth of Popes Creek (Popes Creek Landing) expose glauconitic sand (Nanjemoy) capped by Calvert formation. The contact is 22 feet above the river at the landing, at sea level at a point about 1½ miles south of the landing, where, however, it is covered by alluvium. The bluff just south of the creek shows the following features:

SECTION IN BLUFF JUST SOUTH OF POPES CREEK LANDING, MARYLAND

	Feet	
Calvert formation	25	Sand, very fine with many diatoms
	20	Sand, somewhat coarser with pebbles in base up to 1 inch.
Woodstock member of Nanjemoy formation	3	Sand, dark greenish-brown clay with nodules of pinkish clay in the base.
	5	Sand, glauconitic, dark greenish, gray, fossils in concretions in lower part.
	3½	Greensand, with considerable clay and various fossils. Concretions at base with *Hercoglossa tuomeyi*.
	7	Greensand with some clay; many fossils (according to Clark and Martin) including *Venericardia potapacoensis, Meretrix subimpressa, Hercoglossa tuomeyi, Turritella potomacensis, Mesalia obruta, Protocardia lenis, Modiolus alabamensis, Corbula subengonata,* and *Mitra potomacensis* (zone 17)

The contact here is nearly smooth in general but shows small irregularities, notably tapering holes (worm borings) in the greensand, some of them 15 inches deep, filled with Miocene sediment. A hole bored 22 feet at the base of this cliff was in Nanjemoy greensand; this, together with the outcrop, reveals a thickness of 42 feet at this locality, which, however, is probably less than half its actual thickness to the top of the Marlboro clay member.

Eocene in Virginia

General relations.—It has long been known that strata of Eocene age extend under the Coastal Plain in Virginia. They have been buried by Miocene and later deposits which overlap their western edge but they are extensively bared along all the larger valleys, notably of the Potomac, Rappahannock, Mataponi, Pamunkey, and James rivers. They are comprised in the Pamunkey group which includes the Aquia formation mostly of greensand marl, as the lower half, and the Nanjemoy formation as the upper half, the latter having a basal member, the Marlboro clay, as in Maryland. East of Longitude 77° this member is overlain by 100 or more feet of greensand which thins to the west.

Aquia formation.—The northernmost occurrences of Aquia formation in Virginia are outliers of weathered marl capping the high ridge of Cherry Hill (altitude 165 feet) and other similar ridges (Quantico, Rectory, Decatur) just west of Potomac River from Quantico Creek to Potomac Creek. From Stafford and on the ridges on both sides of Potomac and Accokeek creeks, the Aquia outcrop extends eastward to and down Potomac River. The most extensive exposures are in bluffs along the south side of the lower part of Potomac Creek and extending thence down the south bank of the Potomac River to Chatterton.

South of Aquia Creek the formation slopes below the general county level, but in the valley of the Rappahannock River a wide area is exposed extending to about Latitude 38° 13′, or about 4 miles below Hop Yard where its top passes below sea level. Ledges with *Turritella mortoni* are conspicuous on the Rappahannock River, 2½ miles below Hop Yard wharf, and also near sea level near Fairview on the Potomac River. It is eroded in the deeper part of the valley past Fredericksburg to near

the mouth of Massaponax Creek where its base is at sea level. In the Fredericksburg region the formation lies on arkose, clay, and sandstone of the lowest part of the Potomac group, which was deeply eroded in the long interval of later Cretaceous and earlier Ter-

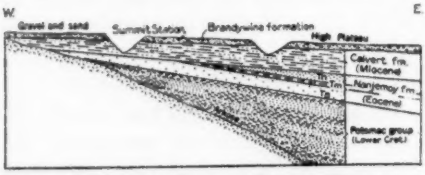

FIGURE 6.—SECTION SHOWING OVERLAP RELATIONS AT THE WESTERN MARGIN OF THE COASTAL PLAIN

Seven miles south of Fredericksburg, Virginia. g, greensand; m, Marlboro clay of the Nanjemoy formation.

tiary time. South of Massaponax its western edge overlaps onto the crystalline rocks. The upper beds are cut by Mataponi River and South River northwest and west of Bowling Green, but the underground relations in that area are not revealed. I described its features at Richmond in 1911.

Nanjemoy formation.—The Marlboro clay member may have been coextensive with the other members of the Eocene succession in Virginia, but it thins to the west, and not far south of Latitude 38° 15′ its western edge is buried under an overlap of Miocene diatomaceous earth which finally extends west onto the upsloping surface of crystalline rocks in the marginal zone southward to and beyond Richmond. The clay passes below sea level a short distance east of Chatterton. It was observed at many places in a wide area south of Potomac River, but I was unable to explore its relations south of Rappahannock River west of Longitude 77° 18′.

The clay is mostly pink or gray and averages about 20 feet thick. The outcrops, with some of the altitudes at the top of the clay, are shown on the map (Pl. 1), but in many wide areas the clay is hidden. Clark and others (1912) refer to this member as "usually consisting of compact white and pink clay in a very persistent layer resting on Aquia greensand." They mention exposures in road cuts on the highway 6 miles north of Fredericksburg and at a point south of Potomac Creek 1½ miles southeast of the railroad. It outcrops at intervals on the ridges south of Stafford, on the slopes south of Potomac Creek, in the plateau west nearly to the railroad, rising gradually to an altitude of 175 feet, from Belvedere Beach to Chatterton, and on the north side of Rappahannock River from a point on the R. F. and P. R. R. southward from Ruff. It was not looked for south of Rappahannock River but it undoubtedly extends south underground as it outcrops on James River southeast of Richmond.

The greensand of the Nanjemoy underlies a wide area in the Coastal Plain in Virginia. Its western edge was not located throughout although I found it did not extend as far west as the Marlboro clay member on which it lies. The thinning to the west is due in part to beveling by pre-Miocene erosion. It thickens eastward to 100 feet or more. Distinctive fossils were observed about Passapatansy and in Caroline County. The upper members of greensand are well exposed at Woodstock (estate) on Potomac River, and the basal bed outcrops at Hop Yard on Rappahannock River. The principal fossils in the lower beds are *Venericardia potapacoensis* and *Corbula oniscus*, and in the upper or Woodstock member there is an extensive fauna, largely distinctive.

The Nanjemoy greensand is widely exposed in the higher slopes east of Fredericksburg (where near Ruff it has an altitude of about 200 feet), to Longitude 77° 4′, where the Calvert contact crosses Rappahannock River about 7 miles below Port Conway. This relation indicates a rate of slope of the truncated surface of about 8½ feet to the mile, the amount increasing considerably to the northwest and west. A broad alluvial flat extends along the river from Mathias Point to a point about 2 miles south of Dahlgren where the upper Nanjemoy passes beneath the Calvert formation at sea level. On the Maryland side of the river the Calvert contact passes below sea level a few miles above Morgantown bridge. The thickness of the formation to the east is not known. Wells near sea level at Colonial Beach penetrated Nanjemoy greensand for about 150 feet and white clay on red clay at depths from 171 to 181 feet, which undoubtedly is the Marlboro member. In these wells water was obtained

in the greensand below a depth of 181 feet, probably in the top of the Aquia formation.

According to Clark and others (1901, p. 81) four species of Protozoa of the Woodstock stage (uppermost Nanjemoy) occur in these wells at 90–92 feet. Fossils of this stage (Clark and others, 1901, p. 81) also were obtained in the Norfolk well at a depth of 685 feet.

MIOCENE

Calvert Formation

General relations.—Deposits of Miocene age occupy a large part of the Coastal Plain of Maryland and Virginia. They are comprised in the Chesapeake Group but of that group only the structure and marginal overlap relations of the lower or Calvert formation are discussed here.

In most of the area the Calvert formation lies unconformably on the Nanjemoy formation of the Pamunkey group (Eocene), and it is overlain unconformably by gravel and sand of the plateau (Brandywine) or by alluvium. To the west it overlaps the thinned-out edges of the Nanjemoy and Aquia formations, the Monmouth and Matawan formations, and the Potomac group, and in places it lies on the old crystalline rocks. The location of its original western margin in Maryland is not determined, because of erosion all along the overlap zone.

The Calvert formation is about 100 feet thick on Chesapeake Bay but thins to the west and north where upper beds have been truncated in late Tertiary and Quaternary times; probably also the formation thinned to the west originally. It comprises several stages which contain distinctive molluscan assemblages, bones, and plants, and the lower part carries a great variety and quantity of diatoms. I did not study the distribution of these fossils or the relations of the several stages. Dryden (1935) mentioned a horizon which contains distinctive fossils.

On hill slopes the Calvert formation is mostly covered by local wash, mainly gravel from the plateau above, or by sand and gravel from the river terrace deposits. In bottoms of valleys it is covered thickly by alluvium which was not shown on the various county maps or on the Patuxent folio all of which show Calvert and Eocene formations bare in the flats above the *theoretical* upper limits of the "Wicomico" and "Talbot" terrace formations. In fact, however, alluvium is dominant in all such places, and it extends continuously from near the heads of all valleys to and below sea level along the river and all the creeks. It is 10 to 40 feet thick and is only cut away in banks at long intervals in the valley bottoms.

Anne Arundel and Calvert counties.—The Calvert formation extends farthest north in Anne Arundel County on the ridge south of the Severn River where thin remnants cap high summits south of Crownsville and about Inglehart. Owing to the low rate of dip it extends far north on the interstream ridges and is cut out far south and east down valleys. Several contacts on weathered greensand of the Nanjemoy formation are exposed, notably one in a road cut 2 miles south by west of Crownsville at an altitude of 155 feet; a dubious one on the railroad just east of Crownsville near 166 feet altitude is the highest one in the county. The contact was also reached in the holes given in Table 5. The basal plane dips southeast at the rate of 10–13 feet to the mile, but the amount and direction vary somewhat.

Calvert beds outcrop under the gravel on the ridge between Patuxent River and Chesapeake Bay. The dip carries their base from an elevation of 150 feet east of Priests Bridge to sea level on a line extending from a point 1 to 2 miles east of Mayo southeast to near Friendship in the southeastern part of the county. This line crosses Patuxent River near White Landing, Latitude 38° 40′. East of Priests Bridge the Calvert formation lies unconformably on Aquia greensand marl, but near Rutland the edge of the Marlboro pink clay member of the Nanjemoy formation comes in, and in a mile or more it overlaps onto the greensand of the Nanjemoy formation which, as stated above, thickens to the east.

The basal contact is not exposed in the Chesapeake Bay slope north of Fairhaven to beyond Rhodes River, but it was reached by several bore holes. A cut just north of the road forks 1.7 miles southeast of Edgewater (4¼ miles east by south of Davidsonville) exposes the nearly level contact at an altitude of near 62 feet of weathered basal Calvert on greensand of the Nanjemoy formation; the latter here

TABLE 5.—HOLES BORED IN THE CALVERT FORMATION IN ANNE ARUNDEL AND CALVERT COUNTIES, MARYLAND

Location	Altitude of ground	Depth of hole	Altitude of base of Calvert	Remarks
Inglehart, 1¼ miles west-southwest	139	10½	130	Greensand (Aquia) 9–10½ feet.
Inglehart, at the station	140	9	131?	To hard bed (base of Calvert?)
Inglehart, ½ mile northwest on road	155	19½	136½	Greensand (Aquia) 18½–19½ feet.
Crownville, ½ mile south-southeast	160	17	144	Greensand (Aquia) 16–17 feet.
Priest Bridge, 2½ miles northeast	164	8	156	Greensand (Aquia) at 8 feet.
Priest Bridge, 2 miles east-northeast at cross road	170	14	157	Greensand (Aquia) 13–14 feet.
Rutland, 1½ miles south	147	19	129	Pink clay (Marlboro) 18–19 feet.
Rutland, 1 mile southeast	150	6	147	Pink clay (Marlboro) 3–6 feet.
Rutland, 1½ miles south-southwest	144	4	140	To Greensand marl (Aquia) (Pink clay absent).
Davidsonville, ½ mile south	136	22	127	Greensand (Nanjemoy) 9–22 feet.
Davidsonville, 2½ miles east by south on road	90	14	81	Greensand (Nanjemoy) 9–14 feet.
Davidsonville 2 miles southwest on road	117	5	115	Greensand (Nanjemoy) 2–5 feet.
Davidsonville, 1½ miles west-southwest on highway, 1½ miles east of bridge	130	21	121	Greensand (Nanjemoy) 9–21 feet. into pink clay (Marlboro)
Davidsonville, 2 miles northwest	140	24	120	Dark clay and sand (Probably Marlboro) 20–24 feet.
Davidsonville, ½ mile west by south on highway	137	12	126	Greensand (Nanjemoy) 11–12 feet.
Davidsonville, 2½ miles south-southwest on road	90	16	75	Greensand (Nanjemoy) 15–16 feet.
Birdsville, ½ mile southeast	71	1	70	Greensand (Nanjemoy) at 1 foot.
Birdsville, 2½ miles northeast	65	17½	61	Greensand (Nanjemoy) 4–17½ feet.
South River Postoffice, ½ mile south	55	21	35	Greensand (Nanjemoy) 20–21 feet.
South River Postoffice, 1½ miles northeast	70?	22	48?	Greensand (Nanjemoy) at 22 feet.
Governors Bridge, 2½ miles east by south on road	126	3	125	Pink clay (Marlboro) 1–3 feet.
Governors Bridge, 2 miles east-northeast	144	11	138	Gray sandy clay (Calvert), 0–6 feet, marl (Aquia) 6–11 feet.
Governors Bridge, 2½ miles east-northeast	137	3	134	Gray sandy clay (Calvert) 0–3 feet to marl (Aquia)
Hills Bridge, 2½ miles northeast	110	24	88	Greensand (Nanjemoy) 22–24 feet.
Hills Bridge, 2½ miles east	100	17	83	Greensand (Nanjemoy) at 17 feet.
Bayard, 3¼ miles east by north	90	22½	68	Greensand (Nanjemoy) 22–22½ feet.

TABLE 5.—(*Continued*)

Location	Altitude of ground	Depth of hole	Altitude of base of Calvert	Remarks
Owensville, 1 mile east	40	3	37	Greensand (Nanjemoy) at 3 feet.
Cumberstone, 1 mile northeast	49	7	42	Greensand (Nanjemoy) at 7 feet.
Galesville, 1½ miles southwest	20	10	15+	Greensand 5 to 10 feet (Nanjemoy?)
Sudley (old postoffice and church)	28	13	15	Hard bed at 13 feet (top of Nanjemoy?)
Pindell, west of station	74	24½	50	Greensand (Nanjemoy) 24–24½ feet.
Dunkirk, 1 mile southeast on south bank of Hall Creek	17	22	−3	Greensand (Nanjemoy) 20–22 feet.

The following holes bored into the Calvert formation failed to reach its base:
Priests Bridge, 2 miles southeast, at 160 feet above sea level; 19 feet.
Birdsville, ½ mile west, at 100 feet; 20 feet.
Hills Bridge, 2 miles east (west of creek) at 105 feet; 15½ feet.
Nutwell, ½ mile south, at 10 feet; 15 feet.
Fairhaven, ½ mile north, at 7 feet above river; 7 feet.
Deal, 1½ miles northwest, at 5 feet above river; 5 feet.
Lower Marlboro at river bank, 20 feet.

is 27 feet thick. The contact is also visible in a cut a few rods south of the road forks, at an altitude of about 57 feet; it shows a decidedly irregular configuration.

In several places in Anne Arundel County the Calvert clay is exposed lying directly on the Marlboro clay. These localities are mostly east and north of Davidsonville beyond the west edge of the greensand of the Nanjemoy formation. There is a good exposure of such a contact on the road 1.6 miles north-northeast of Davidsonville at 140 feet above sea level.

Calvert, lying on the irregular surface of greensand of the Nanjemoy formation, is well exposed in road cuts three quarters of a mile north-northeast of former South River post office a few rods southwest of the fork of the road to Mayo, at an altitude near 57 feet, and also in a cut bank just north of that fork, where it is about 5 feet higher. This contact is also exposed on the road on the slope just west of Contee's Wharf, at an altitude of about 50 feet. On the highway where it crosses Lyons Creek wharf, the contact is well exposed at an altitude of 45 feet. It is 15 feet above the river in the fine exposure at the "silica mine" just north of oldr Fery Landing, and it passes below the river (sea level) half a mile above White Landing. A 20-foot hole on the river shore at Lower Marlboro landing failed to reach it. In all these contacts the Calvert is on greensand of the Nanjemoy formation which may be 100 feet thick at Lower Marlboro.

The basal contact of the Calvert was reached by many holes bored in Anne Arundel County so that a fairly accurate contour map could be constructed (Pl. 1).

Prince Georges County.—The Calvert formation occupies a wide area in Prince Georges County, underlying all of the gravel-capped plateau, and, as this latter becomes higher to the north, the Calvert extends out along the higher interstream ridges in outliers, to near the latitude of Collington. It is widely trenched by the valleys of Patuxent River, Collington Branch, and Northwest Branch and cut back or deeply notched by valleys leading to the west into Anacostia and Potomac rivers. It rises high in the divide ridge east of Anacostia River where, in Good Hope Hill in the east side of the District of Columbia, it lies on Monmouth formation at an altitude of 221

feet. East of Good Hope Hill the Calvert formation lies on the Aquia formation and crops out in a zone a mile or more wide; thence, eastward it overlaps across the edge of the Nanjemoy formation. West of the valleys of the Anacostia and Potomac rivers it lies on the Potomac group in part and also overlaps onto gneiss.

The Calvert formation thins to the north and west, apparently by truncation, down to lower and lower horizons prior to the deposition of the gravel and sand of the Brandywine formation, and in outlying remnants of the high plateau it has been entirely removed. On the ridge between Patuxent River and Northwest Branch there are many exposures of the Calvert beds lying on Eocene. One, in a road cut 1½ miles east-southeast of Mitchellville post office just east of Crain Highway, shows Calvert sandy clay on gray and pink Marlboro clay (11 feet thick) at an altitude of 134 feet. A mile farther south on Central Avenue just west of Crain Highway the basal Calvert contact is at 125 feet. In a cut on the highway half a mile west of Hills Bridge the contact of light-gray Calvert clay, with some gravel, and Nanjemoy greensand is at 90 feet, and 1 mile southeast of Leeland there is a similar contact at 122 feet above sea level. On the road half a mile east of Marlboro it is at 94 feet.

Contacts at the base of the Calvert are exposed in cuts on the highway to Washington 2 miles west of Marlboro at an altitude of 125 feet, 1½ miles west by north of Marlboro on the road to Ritchie at 123 feet, on the road 1¼ miles south-southwest of Marlboro at 104 feet, on the road three quarters of a mile southwest of Marlboro at 116 feet, and in road cuts 2 miles south-southwest of Marlboro at 95 feet.

A cut on the main highway half a mile east of the eastern part of Marlboro exposes about 21 feet of greensand (Nanjemoy) up to a contact near 94 feet above sea level. In the cut in the highway about half a mile west of Hills Bridge, where the greensand (Nanjemoy) is about 55 feet thick, the contact is near an altitude of 90 feet. The contact is obscure in road cuts east of Hall Station at an altitude near 150 feet; here the Nanjemoy greensand is thin. In the outlier of Calvert formation 2½ miles west-northwest of Governor Bridge it lies directly on Aquia marl at an altitude of 200 feet. The downslope of the contact to the southeast is about 150 feet in a distance of 10 miles in this region.

A road cut half a mile north-northwest of Marlboro exposes the contact at an altitude of 110 feet, and another one 3 miles north is at 127 feet. The contact is near an altitude of 142 feet in Foxden Hill, an outlier 2½ miles west-southwest of Leeland. It is at 160 feet on the road 1¼ miles northwest of Hall Station, at 200 feet in the outlier 3 miles east-southeast of Ardmore, and at 210 feet on Defense Highway, 1.6 miles west of Collington. Just east of Largo the cut of Central Avenue exposes the contact at an altitude of 178 feet. It is also exposed in road cuts at several places near Croom Station, half a mile northeast of that place at an altitude of 95 feet. Another contact exposed 1¾ miles west by north of Croom is at 110 feet, and a third, a quarter of a mile east of that station, on an old road, is at an altitude of 97 feet.

Old railroad cuts 2⅝ miles southeast of Ritchie show the contact of Calvert on pink clay (Marlboro). Other exposures of this relation are 1 mile southwest of Ritchie in a road cut at 185 feet above sea level, or about 35 feet above the creek, at the school half a mile farther southeast at 180 feet, and in old railroad and road cuts 1½ miles south-southeast of Ritchie at an altitude of 170 feet.

North and west of a line joining Hall Station and Forestville and its projection nearly to Fort Washington, the Marlboro pink clay and the greensand of the Nanjemoy formation are absent, and the Calvert formation overlaps directly onto greensand marl of the Aquia formation, but east and south of that line the Marlboro pink clay or overlying greensand of the Nanjemoy formation intervenes. The general downslope to the southeast is at a rate of about 8 feet to the mile, and in general it is both regular and smooth. One marked irregularity, apparently due to channeling in Miocene time, is exposed on the Crain highway just south of Charles Branch, 1½ miles west of Croom.

There are many exposures of the Calvert formation in the higher slopes of Good Hope

TABLE 6.—HOLES BORED IN CALVERT FORMATION IN PRINCE GEORGES COUNTY, MARYLAND

Location	Altitude of ground	Depth of hole	Altitude of base of Calvert	Remarks
Governors Bridge, 2¼ miles west, on road	190	7	184	Greensand (Aquia) 6–7 feet.
Mitchellville post office (1 mile south-southeast of Mulliken Station	156	12	150	Pink clay (Marlboro) 6–12 feet.
Mitchellville post office, 2⅛ miles southeast of	117	12	105	Into pink clay.
Mitchellville post office, 1¼ miles southeast on highway	137	9	129	Pink clay 8–9 feet (Marlboro).
Halls Station, 2¼ miles east (1¼ miles west of river)	145	16½	138	Greensand (Nanjemoy) 6½-16 feet.
Halls Station, 1 mile north-northeast	156	12	150	Pink clay 6–12 feet (Marlboro).
Halls Station, ¾ mile west (on road)	148	7	141	Greensand (Nanjemoy) at 7 feet.
Hills Bridge, ½ mile west (south of road)	118	24	94	To Greensand (Nanjemoy) at bottom.
Leeland, 1 mile west-southwest, (¼ mile south of St. Barnabas Church)	150	11	140	Greensand 10–11 feet.
Leeland, 1 mile north-northwest	136	14½	130	Pink clay (Marlboro) 8–14½ feet.
Leeland, Foxden Hill, 2⅓ miles southwest	157	17	142	Pink clay (Marlboro) 15–17 feet.
Leeland, ½ mile east on road	137	17	131	Greensand 6–17 feet.
Leeland, 2.6 miles east	109	14	95	Greensand at 14 feet.
Marlboro, 2¾ miles west-northwest on road	150	14	144	Greensand (Nanjemoy) 6–14 feet.
Marlboro, 3½ miles southwest. On side road	120	21	113	Greensand (Nanjemoy) 7–21 feet.
Marlboro, 1¾ miles south-southeast on P.R.R.	100	16½	85	Greensand (Nanjemoy) 15–16 feet.
Marlboro, 1½ miles north, on road	132	4	128	To greensand (Nanjemoy).
Marlboro, 3 miles north by west, on road	130	3	127	To greensand (Nanjemoy).
Marlboro, 2½ miles northeast on Hill farm	91	7	84	To greensand (Nanjemoy).
Croom Station, P.R.R., 1¼ miles west by north, on old road	114	6	108	To greensand (Nanjemoy).
Croom Station, P.R.R., 1¾ miles west on highway	119	10	109	To greensand (Nanjemoy).
Croom Station, P.R.R., 2¼ miles northwest, north of branch	120	21	113	To greensand (Nanjemoy) 7–21 feet.
Croom Post office, 1½ miles east-northeast	93	3	90	To greensand (Nanjemoy).

TABLE 6.—(*Continued*)

Location	Altitude of ground	Depth of hole	Altitude of base of Calvert	Remarks
Croom Post office, 2 miles northeast	94	4	90	To greensand (Nanjemoy).
Ritchie, 1½ miles southeast	164	6½	158	To greensand (Aquia).
Seat Pleasant (old), 1 mile south-southwest	208	14½	194	Greensand (Aquia) 14–14½ feet.
Seat Pleasant (old), ½ mile east	201	9½	192	Greensand (Aquia) 9–9½ feet.
Forestville, 3½ miles east (Westphalia school)	155	9	146	To pink clay (Marlboro).
Forestville, 1½ miles northwest, (15 feet above creek)	200	19	185	Olive clay 0–15 feet, dark sandy marl (probably Aquia), 15–19 feet.
Cheltenham, 1 mile nw. on road to Woodyard	170	27	143?	To hard bed (probably Nanjemoy).
Cheltenham, 2½ miles east by south on road	100	23½	—	All Calvert.
Cheltenham, 2½ miles east-southeast on road	128	23	—	All Calvert.
Cheltenham, 5 miles southeast on Rock Creek	60	13	—	All Calvert to hard bed.
Cheltenham, 2 1/10 miles west (north of creek near road)	150	22	129	Greensand (Nanjemoy) 21–22 feet.
Largo, ¼ mile west on Central Avenue	191	9	183	Greensand (Nanjemoy) 8–9 feet.
Largo, ¼ mile east on Central Avenue	180	4	178	Greensand (Nanjemoy) 2–4 feet.
Drury, 1 mile east, main road	100	17	83	Greensand (Nanjemoy) 17 feet.
Woodyard, on road near creek	194	18	—	Olive clay, all Calvert.
Woodyard, 1½ miles northeast	160	20½	142	Greensand (Nanjemoy) 18–20½ feet.
Bradbury Heights, 1 mile south	211	17½	202	Dark sand (Aquia)? 9–17 feet to hard bed at 17½ feet.
Bradbury Heights, 1 mile south	224	23	201	Calvert fine olive clay to hard bed (Aquia?) at 23 feet.
Oakland, 1½ miles west-northwest	225	29	197½	Dark sand (Aquia?) 27½–29 feet.
Oakland, 2 miles northwest	225	31	198	Dark sand (Aquia?) 27–31 feet.
Pine Grove school, 1 mile northeast on road	217	25	195	Greensand (Aquia) 22–25 feet.
Pine Grove school, ½ mile northeast	195	6	190	Greensand (Aquia) 5–6 feet.
Seat Pleasant (old manor), 8 miles south-southwest near longitude 76° 52′ 30″	210	16½	194	Greensand (Aquia) 16–16½ feet.
Seat Pleasant, ¾ mile north near triangulation sta.	258	17	241½	Greensand (Aquia) 16½–17 feet.
Capitol Heights, 1 mile south, at water tank	219	21	199	Greensand (Aquia) 20–21 feet.
Capitol Heights, .4 mile north	235	21	215	Greensand (Aquia) 20–21 feet.
Suitland, 1½ miles east on road	206	34	173	Greensand (Aquia) 33–34 feet.
Ridge Road, 1¾ miles south-southeast of Bennings Station	200	18	184	Hard Magothy 16–18 feet.

TABLE 6.—*(Continued)*

Location	Altitude of ground	Depth of hole	Altitude of base of Calvert	Remarks
Burns Street, just south of Hillside Road	210	8	203	Variegated clay (Raritan) 7–8 feet.
Alabama Avenue, just west of Hillside Road	205	8	198	Variegated clay (Raritan) 7–8 feet.
Massachusetts Avenue (extended)	190	13	184	Clay (Calvert)? 0–6 feet.
Massachusetts Avenue (extended), a few rods farther south at a spring	165	6	159	To black sand, micaceous. (Monmouth).
Walker Road, just west of 30th Street, southeast	218	29	196	In black sand, micaceous, (Monmouth) 22–29 feet.
2809 30th Street, S.E., 600 feet south of Walker Road ¾ mile south of Good Hope crossroads	207	22	186	Possibly Aquia 21–22 feet, to Monmouth.
Camp Springs, 1½ miles west by south, on road to St. Ignatius church	164	20	145	Greensand (presumably Aquia) 19–20 feet.
Camp Springs, $1\frac{1}{10}$ miles northwest, on creek	173	17	165	Tough gray clay (Calvert probably) 0–8 feet, greensand (Aquia) 8–17 feet.
St. Ignatius Church, just northeast, on road	182	11	172	Greensand (Aquia) 10–11 feet.
Oxon Hill Post office, ½ mile southeast	190	19	172	Greensand (Aquia) 18–19 feet.
Oxon Hill Post office, 1.8 miles southeast, on road ½ mile south of Henson Creek bridge	182	24	165	Dark sand (probably Nanjemoy) 17–24 feet, on black marl.
Silver Hill, ½ mile west in deep valley	200	16	185	Greensand (Aquia) 15–16 feet.
St. Barnabas Church, 1½ miles east by south	179	6	174	Greensand (Aquia) 5–6 feet.
Tinkers Creek, 6 miles west by south of Clinton, on road, 12 feet above creek	157	12	152	Pink clay (Marlboro) 5–17 feet.
TB, 2.1 miles northwest on Southern Maryland highway	152	33	—	All Calvert.
TB, 2.2 miles northwest, 200 yards south of creek	112	5	107	To greensand (Nanjemoy).
Locust Grove School, ¾ mile south, (2½ miles south of Padgett Corners)	180	34	—	All Calvert
Piscataway, ½ mile east-southeast	114	4	110	To greensand (Nanjemoy).
Piscataway, 1¾ miles northwest	129	24	118	Pink clay (Nanjemoy) 12–24 feet.

TABLE 6.—(*Continued*)

Location	Altitude of ground	Depth of hole	Altitude of base of Calvert	Remarks
Piscataway, 4½ miles northeast, south of creek	112	2	110	To greensand (Nanjemoy) at 2 feet.
Piscataway, ½ mile east by south	122	12	110	To greensand (Nanjemoy) at 12 feet.
Piscataway, 1¾ miles northeast near Old Thrift	120	12	108	To greensand (Nanjemoy) at 12 feet.
Piscataway, 1 mile north-northeast	133	9	126	Also a contact on creek at 126 feet.
Piscataway, 2 miles north by west	143	9	137	Greensand (Nanjemoy) 6–9 feet.
Piscataway, 2½ miles southwest on west side of highway	130	18	113	Greensand (Nanjemoy) 17–18 feet.
Accokeek, 2 miles east by south	125	7	118	To greensand (Nanjemoy).
Accokeek, 2 miles southeast	90	4	86	To greensand
White Landing, bank of Patuxent River	0	1½	−1	On greensand (Nanjemoy).
Nottingham, 1.8 miles southwest near Rock Creek	25	12	?	To hard bed, possibly basal Calvert.

Hill east and northeast of Anacostia, and it underlies all the high plateau region southeast of there. The basal contact is visible in road cuts, those to the west and north mostly on Monmouth formation, and those to the southeast on the thinning western edge of the greensand marl of the Aquia formation. On the 228-foot hill just south of D. C. milestone No. 1, or just east of 54 Street and Drake Place, a 23-foot hole at an altitude of 223 feet penetrated 6 feet of Calvert formation lying on 17 feet of Monmouth beds (with base at 200 feet), constituting an outlier. A similar hill at the crossing of the D. C. line by Fitch Street probably has the same constitution, but the Calvert, if present, is hidden by gravel; the Monmouth is exposed here, and a 7-foot hole by the road at this place reached white clay (Raritan). On Bennings Road a contact is exposed at 205 feet on red variegated clay (Raritan). Near the corner of 44 and Hanna streets, and of Ridge Road and Burns Street, the altitude of the contact is 195 feet. In an outlier on Ridge Road about 300 yards west of Burns Street it is at 185 feet. On Massachusetts Avenue extended, the contact slopes from 189 to 200 feet in a short distance, and in an outlier on the south side of Pennsylvania Avenue just west of Branch Avenue it is at 200 feet (on Monmouth formation). On Hillcrest Road northwest of the corner of W Street, the Calvert-Monmouth contact is at an altitude of 193 feet, and on Fort Baker Drive at 195 feet.

On the north side of Good Hope Road east of Anacostia there has been for many years an extensive cut in Calvert beds (Fig. 2). Calvert lies on 4½ feet of micaceous black sand (Monmouth) at an altitude of 220 feet; in a gully three quarters of a mile northeast of Good Hope cross roads, there is a contact at 194 feet.

At the Orloff sand pit the Calvert formation is part of a troublesome overburden. The contact here is near an altitude of 196 feet with 5–6 feet of Monmouth formation below (Fig. 3). The Calvert, a dark-gray sandy clay, is 20 feet thick below the gravel which caps a plateau remnant.

The valley of Oxon Run cuts deeply into the Calvert formation and reveals the underlying Potomac formation for some distance, but the contact is visible at but few places. In road cuts 2½ miles southeast of Oxon Hill, and again

1½ miles southeast, the contact on Aquia shell marl is exposed.

Near old Seat Pleasant (manor), Central Avenue exposes the Calvert contact at several places. The first exposure from the west is about 2 miles east of the District line or slightly more than half a mile east of Cabin Branch. Here at an altitude of 215 feet the light-colored weathered Calvert contrasts strongly with the brown-weathered glauconitic sand of the Aquia formation. This contact, at a slightly lower altitude, is again visible in the next cut about 800 yards east of the road forks and in the cut just west of the road to Ritchie at an altitude of 192 feet. The rate of slope indicated is nearly 50 feet to the mile. The contact is also exposed in the old Chesapeake Beach railroad cut a short distance south of Central Avenue, at 210 feet above sea level.

In canyons in the northern margin of the plateau there are several good contacts. One on the creek a quarter of a mile to the west, slightly north of Pine Grove school, is near 195 feet, and another in the next gully north is at 200 feet. On the creek a mile southeast of Silver Hill there is an exposure of the basal contact at an altitude of 180 feet.

Henson Creek valley is deep beyond Latitude 38° 45′ 50″, and the Calvert-Aquia contact is exposed in cuts in various roads that cross it and along banks of some of its larger branches. A quarter of a mile southwest of Saint Ignatius church and in cuts a mile to the southwest, contacts of Calvert on Aquia shell marl are exposed.

A contact of Calvert on greensand of the Nanjemoy formation is exposed in a road cut 2½ miles west of T. B. at 115 feet, and there is another one 3 miles northwest of T. B. at an altitude of 120 feet, both on slopes into Piscataway Creek. Half a mile northeast of Friendly a contact of Calvert clay on pink clay (Marlboro) is exposed at 150 feet above sea level; the latter formation was bored into 22 feet. On the Suitland Road at the District line the Calvert clay lies on the Aquia formation at 204 feet, and on Branch Avenue, a few hundred yards east of the District line, this contact is near 200 feet, a short distance below a thin remnant of terrace gravel. A mile southwest of Farmington Landing a contact is exposed in a road cut at an altitude of 115 feet, and in a near-by gully at 106 feet.

Charles County.—The Calvert formation extends across Charles County, but most of its bevelled-off western margin is buried and overlapped by gravel and sand of the Brandywine formation. It has been removed by erosion in the wide trough of the valley of Potomac River and it is deeply incised by the valleys of Mattawoman and Port Tobacco creeks and Mill and Ward runs. Its base reaches sea level along a line passing not far west of Hughesville and Dentsville and reaching Potomac River nearly 4 miles below Popes Creek. It slopes southeast at a rate of about 10 feet to the mile, with some marked variations between Accokeek and Waldorf. The valley of Zekiah Swamp doubtless has been cut slightly into the underlying Nanjemoy formation, but the bottom of this valley extending across the county now contains thick alluvium which hides the subterrain. A 36-foot boring low in this valley 4 miles west-northwest of Hughesville was all in Calvert beds to an altitude of about 64 feet without reaching their bottom. The top of the Nanjemoy formation here is at an altitude of about 30 feet. A 37½-foot hole bored to an altitude of about 25 feet just east of Newton and a hole bored to near 60 feet above sea level on Clark Run, 2 miles northeast of Bel Alton, also failed to reach the base of the Calvert formation. The record of the 631-foot well at La Plata did not report the depth to the base of the Calvert formation which was probably near 120 feet.

On the road from Bryans Road to Marshall Hall weathered Calvert clay is exposed from an altitude of 120 feet up to 160 feet, and it also appears in road cuts 1¼ miles southwest of Bryans Road, both on the slope into the Potomac Valley. Basal contacts are exposed in road cuts and gullies in the Mattawoman Creek ridge. On the opposite or southeast side of this valley basal contacts are exposed at an altitude of 119 feet, on the road 2½ miles southeast of Bryans Road, and at an altitude of 123 feet on the road seven eighths of a mile northwest of Pomfret. Basal contacts in cuts of the road crossing Ward Run near Hilltop are at an altitude of 105 feet on both sides of the valley and also on the same road in a cut just east of Welcome. A cut 1¼ miles east-southeast of

TABLE 7.—HOLES BORED IN CALVERT FORMATION IN CHARLES COUNTY, MARYLAND

Location	Altitude of ground	Depth of hole	Altitude base of Calvert	Remarks
Bryans Road, 1½ miles north by west road cut	130	17	114	In dark sand probably Aquia.
Bryans Road, 1¼ miles southwest road cut	150	37	113	In dark sand probably Nanjemoy.
Bryans Road, 1⅜ miles southwest road cut	115	17½	113	0–2 feet Calvert.
Benville, 2 miles north on road	90	4	86	To greensand (Nanjemoy) at 4 feet deep.
Troy (Berry), ½ mile northwest on south side of Mattawoman Creek	133	27	107	23 feet above creek. Into Nanjemoy several inches.
Pomonkey, 1¾ miles south by west road cut	130	15	115	To greensand (Nanjemoy).
Mason Springs, ½ mile southwest road cut	127	13	114	Near base of Calvert.
Pomfret, 1½ miles northeast on road	140	20	121	Greensand (Nanjemoy) 19–20 feet.
Pomfret, 2½ miles south by east on road to La Plata	135	30	108	94 feet above Port Tobacco Creek. 27–30 feet shell marl (Nanjemoy).
Mt. Pisgah, 1¼ miles southeast on road to Port Tobacco	115	22	93	To hard bed probably top of Nanjemoy. Contact in gulley near by at 90 feet above sea level.
Welcome, 1½ miles east by south road cut	80	8	72	0–8 Calvert on dark greensand (Nanjemoy).
Chapel Point, ¼ mile east of road forks	78	11	68	On greensand (Nanjemoy) 10–11 feet.

Additional Calvert-Nanjemoy contacts observed in road cuts in Charles County, Maryland

Location	Altitude
Bryans Road, 1½ miles southwest	113
Bryans Road, 1½ miles southeast	121
Bryans Road, 2 miles southeast	119
Pomonkey, 1 mile southeast	120
Pomonkey, 1¾ miles south by west	119
Mason Springs, ½ mile southwest	114
Mason Springs, 2 miles southeast	116
Mt. Pisgah, 1¼ miles southeast, in gulley north of road	90
Port Tobacco, 2½ miles north by west	106
Port Tobacco, 1½ miles northeast	73
Port Tobacco, ½ mile northwest	68
Hilltop, ½ mile southwest, also just north	105
Hilltop, 1 mile east	100
Welcome, ¼ mile east	100
Chapel Point, 1 mile west	62
Popes Creek Landing, river bank	22–17

Welcome exposes the contact at an altitude of 72 feet, and in a cut a mile farther southeast it has sloped down to 62 feet.

In the valley of Port Tobacco Creek the base of the Calvert formation is exposed at a few places, and it was reached by several bore holes. Near the creek half a mile north-northwest of Port Tobacco the altitude of the contact is 68 feet, and on the road cut in a side valley 1¼ miles southwest of La Plata it is exposed at 73 feet above sea level.

The exposures in the river banks above and below Popes Creek Landing are extensive. One just below the mouth of the creek shows a strong contrast of the light-gray Calvert deposit on the dark glauconitic sand of the Nanjemoy formation at 22 feet above sea level.

The extent to which the plateau southwest of Mason Spring about Pisgah and Doncaster is occupied by Calvert beds is not known because of the covering of gravel and sand. Calvert deposits are present in the slope half a mile southwest of Mason Spring, and the land southward about Pisgah appears to be high enough to carry a thin cap of Calvert formation under the gravel mantle. A 17½-foot hole on Stretchmark Hill just south of Doncaster is entirely in pinkish clay which probably is Marlboro because it contains no diatoms nor other Miocene organisms.

Several holes into Calvert formation failed to reach its base.

They were as follows:

	Altitude (Feet)	*Depth (Feet)*
Priests Bridge, 2 miles southeast	160	19
Birdsville, ½ mile west	100	20
Hills Bridge, 2 miles east (west of creek)	105	15½
Nutwell, ½ mile south	10	15
Fairhaven, ½ mile north	7	7
Deal, 1½ miles northwest	5	5
Lower Marlboro at river bank		20

Outliers of Miocene and Pliocene

General relations.—Thin bodies of fine yellow loamy sand overlain by gravel cap many ridges west of the margin of the main body of Coastal Plain deposits in Maryland and Virginia. Most of them are on the gneiss, but in places they are underlain by distinctive Potomac gravel or arkose in outliers or extending up interstream ridges. The writer believes these sands are of Miocene age (Calvert) protected by gravel (Brandywine) of the old high gravel plain which originally extended over the region. They represent westerly extensions of this plain and are at altitudes in close accord with its rate of upward slope to the west as shown on Plate 1. They are all on or west of the so-called "Fall Line".

In Washington there is a large outlier at Soldiers Home (Pls. 2, 3) where the material closely resembles the weathered phase of the Calvert that occurs in the high plateau extending south and east of Good Hope Hill. In northern Virginia a few dim shell impressions observed in the sand appear to be Calvert. Farther south near Latitude 38° 12′ well-characterized Miocene deposits with Calvert fossils overlap onto the gneiss up to an altitude of about 170 feet. The bases of the highest outliers in northern Virginia reach an altitude slightly above 500 feet, the one at Tenley near Washington is near 400 feet, and most of those west and north of Baltimore are 400 to 500 feet. An outlier near Berea north of Fredericksburg is at an altitude of 285 feet. The contours on the map (Pl. 1) show the configuration of the base of the Miocene deposits as determined by outcrops and bore holes. Undoubtedly these deposits extended farther west, and their western margin was removed by post-Pliocene erosion. The gravel capping summits north of Susquehanna River appear to be outliers of the uplifted high plateau, most of them lying on thin remnants of Potomac formation, in places with fine-grained Miocene deposits intervening. In Egg Hill, 5 miles northwest of Elkton, where the altitude at the top is 442 feet, the sand cap is apparently the upper part of the Potomac group. A hole on Black Hill entered buff fine sand regarded as Matawan, underlain by conglomerate thought to be Magothy formaerate thought possibly to be Magothy formation. Gravel-capped hills at altitudes of 420 feet near Webster, 340 feet near Carsins, 400 feet at Mountain, and 480 feet west of Cub Hill probably are Brandywine of the old high plain. In a 10-foot hole bored in a gravel pit 3 miles east of Towson, the gravel is underlain at 480 feet by soft yellow sand and clay re-

sembling Miocene; but no direct evidence of age was obtained; it may be Potomac or even Upper Cretaceous.

Maryland.—The plateau remnant at Catonsville, the surface of which attains a maximum elevation of 528 feet, is covered by high-plain gravel (Brandywine). This is underlain in part by reddish-brown loam decidedly like weathered Calvert, which to the eastward is underlain by arkose and red sandy clay of the Potomac group. A 19-foot hole bored at No. 431 Ingleside Avenue, half a mile northeast of B. M. 508, at an elevation of about 480 feet, at the base of the gravel cap, passed through yellow loam and soft mealy moulding sand from 0–13 feet (probably Calvert) and sharp brown sand with a few pebbles, probably Potomac, from 13–18 feet, below which was gneiss. The yellowish loam outcropping at various places in slopes and gullies in the Catonsville upland is a thin remnant protected by the overlying Brandywine which is decidedly resistant to erosion. I mapped it as Miocene (Calvert) in 1892.

Several summits on the ridge between Patapsco and Patuxent rivers are capped by gravel (Brandywine) remnants of the Brandywine high plateau. In places this is underlain by yellow sandy clays (doubtless Miocene) lying on thin Potomac remnants or directly on crystalline rock. Six feet of this material was penetrated in a hole half a mile west of Jonestown. Eighteen feet of it was penetrated in a hole 1½ miles east-northeast of Jonestown, lying on rotted granite, and 20 feet of it is exposed in a road cut a mile east of Jonestown (450–470 feet) lying on pink and gray clay of the Potomac group. Other exposures of this Miocene are in road cuts farther east and south near an altitude of 400 feet.

A thin wedge of this yellow loam appears between the Potomac sand and Brandywine gravel in road cuts 2¾ miles west by north of Savage Station at an altitude of 360 feet. At Willis School 2½ miles west of Laurel similar loam appears at 359 feet, lying on Potomac gravel, and at 440 feet on the same road a 6-foot hole was bored through it into granite; above this hole 6 feet of the loam is exposed in the road cut.

Gravel-covered plateau remnants constitute the higher summits of the Piedmont area from White Oak to beyond Burtonsville, but in these the gravel appears to lie on schist, with no Calvert present. A 10-foot hole on the road 1½ miles east of Burtonsville penetrated moulding sand on buff clay, both doubtless Calvert. About 1 mile southeast of White Oak, at an altitude of 360 feet, a road cut exposes fine buff sand which probably is Calvert.

District of Columbia.—The outliers of the high plateau gravel north and west of Washington constitute summits at Soldiers Home, Silver Spring, Fort Totten, and Tenleytown. They lie on an upslope projected from the Calvert-Brandywine contact plane in Good Hope Hill that extends so widely to the east and south under the plateau area of the Coastal Plain of east-central Maryland (Pls. 1, 2).

There are two formations in these outliers. The upper one, of red loam gravel, believed to be Brandywine[4] such as covers the plateau to the southeast (long known and mapped as Lafayette), is in part underlain by a fine buff clayey sand closely resembling weathered Calvert outcrops. The plateau remnants around Silver Spring and Takoma Park consist of old gravel (Brandywine) mostly underlain by Potomac deposits, but in places also overlapping directly onto schists. Their altitude is about 350 feet. At Soldiers Home a thick remnant of the Brandywine gravel-capped plateau has an altitude of 350 feet. It contains a wedge-shaped mass several feet thick, of fine rather bright-yellow clayey sand which appears to be Calvert, lying on distinctive lower Potomac clay and

[4] Most of the gravel deposits above 300 feet are now classified as Bryn Mawr.—C. W. Cooke

PLATE 2.—OUTCROPS

FIGURE 1.—CALVERT, MONMOUTH, AND MAGOTHY FORMATIONS
Good Hope road (Marlboro Pike), east of Anacostia

FIGURE 2.—BRANDYWINE GRAVEL ON CALVERT FORMATIONS
Just west of Soldires Home, on Upshur Street west of Third Street, N. W. Washington

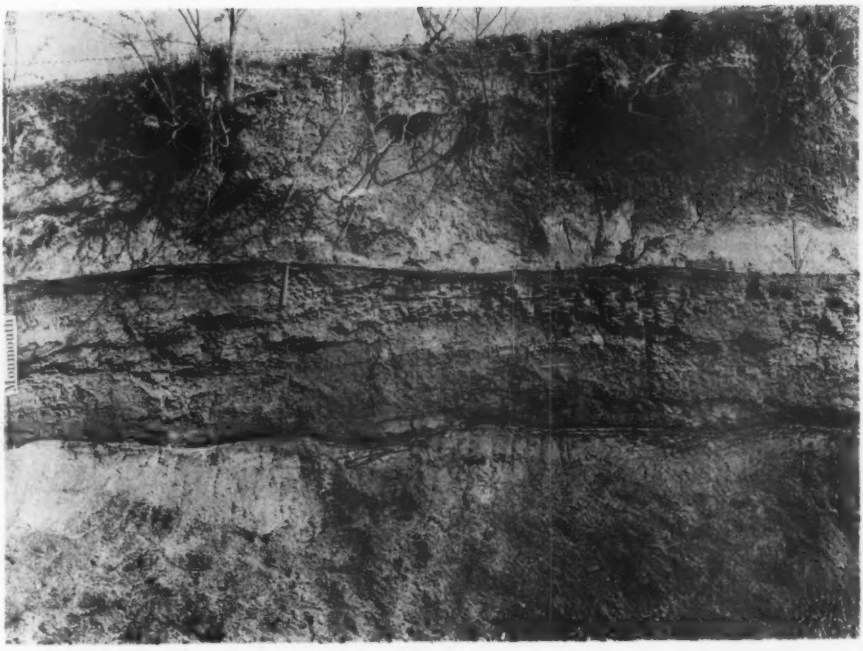

FIGURE 1

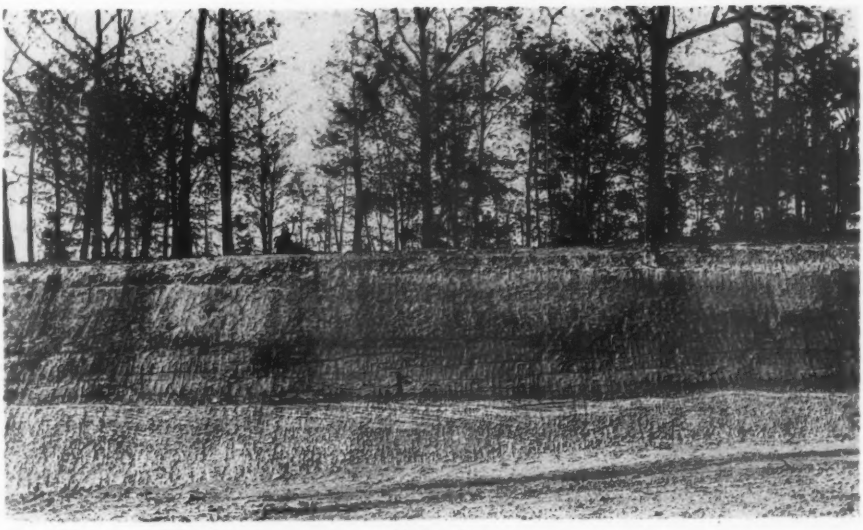

FIGURE 2

OUTCROPS

FIGURE 1

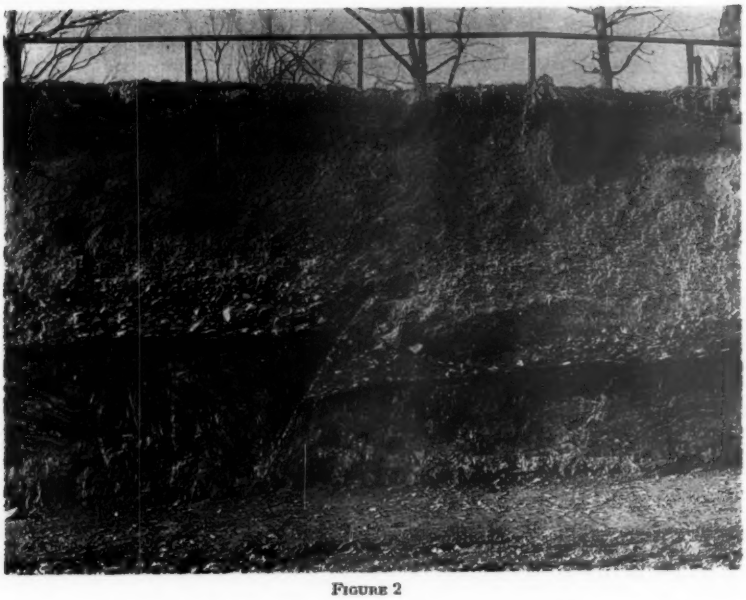

FIGURE 2

OUTCROPS

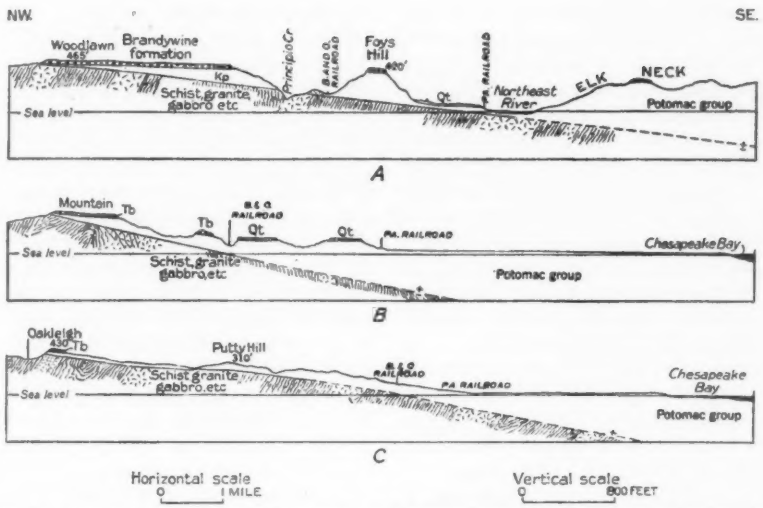

FIGURE 7.—SECTIONS OF TERTIARY OUTLIERS ON NORTHWESTERN MARGIN OF THE COASTAL PLAIN IN NORTHERN MARYLAND

Tl Gravel cap. Qt Terrace gravels.
Section A—Through Woodland and Foys Hill and Elks Neck.
Section B—From Mountain eastward to Chesapeake Bay.
Section C—From Oakleigh eastward to Chesapeake Bay.

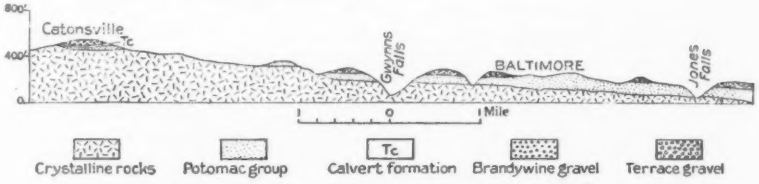

FIGURE 8.—SECTION FROM CATONSVILLE THROUGH BALTIMORE, MD.
Showing relations of sedimentary deposits.

arkose. After 1930 most of this area was sloped and sodded so that the relations are no longer visible.

The principal exposure near Soldiers Home, in 1900 and a few years following, was in a high bank on Upshur Street west of Second Street, N.W., about 200 yards west of the (home) building, where the top of the plateau has an altitude of 315 feet (Pl. 2, fig. 2; Pl. 3, fig. 1). At the top is 12 feet of gravel, mostly quartzite, in a reddish loam matrix in an irregular area about 2500 feet long from east to west, by 2000 feet wide. It has a slightly rolling plateau surface with highest parts near 320 feet in altitude. The underlying formation is fine buff clayey sand (Calvert). Potomac arkose underlies the Calvert formation at Upshur Street to a thickness of about 150 feet, but the location of the

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PLATE 3.—OUTCROPS

FIGURE 1.—BRANDYWINE GRAVEL ON CALVERT FORMATION
West of Soldiers Home, on Upshur Street just west of Second Street, N. W., Washington

FIGURE 2.—FAULT IN TERRACE GRAVEL ON GNEISS
Calvert Street, Washington, looking north

western edge of the Calvert is not known precisely. In 1933 there were good exposures of the buff sand (Calvert) on New Hampshire Avenue just south of Decatur Street, showing 6 feet of it between the Brandywine gravel cap above and Potomac arkosic sand beneath. A small gravel-capped outlier a short distance north of the Soldiers Home area is surmounted by the old earthworks of Fort Totten at 320 feet altitude. Gravel and sand, some with an orange-loam matrix, caps the plateau divide between Rock Creek and Sligo Branch, between Silver Spring, Walter Reed Hospital, and Takoma, and there are some outliers of the same character on highlands south and east of Takoma. This remnantial area extends west nearly to Sixteenth Street near Dogwood Street and Holly Street, where the altitude exceeds 360 feet, and east along the Silver Spring ridge road nearly to its junction with Blair Road at an altitude of 290 feet. The surface is a plateau, somewhat rolling, and the capping material resembles the gravel cap at Soldiers Home and on the ridge at White Oak. This gravel lies in part on gneiss and in part on remnants of a gravelly member of the Potomac group, in places overlapping the latter onto gneiss. Years ago it was thought to be Potomac, but its aspect and relations indicate that most if not all of the higher areas are remnants of the original Coastal Plain plateau, of Brandywine formation.

The Tenleytown ridge which is followed by Rockville Road (now Wisconsin Avenue) from north of Georgetown to Tenleytown, and also by Nebraska Avenue, consists of a long narrow V-shaped remnant of the Brandywine high plain. The surface slopes from an altitude of 356 feet at its southern edge at Mount Alto hospital, to 415 feet at its north end at Reno reservoir at Tenleytown, a distance of 2 miles. It is a slightly rolling plateau with the eroded edges abrupt at most places. North and west of the crest at Tenleytown (Reno) the plateau slopes down 100 feet or more into a hilly region of gneiss which does not attain an altitude as high as 400 feet in several miles. Near Mount Alto hospital the base of the Calvert is near 335 feet, and in Tenleytown, 2 miles farther north, it is near 396 feet, a slope of 61 feet, which is considerably steeper than shown in the slope in Good Hill and the plateau region to the east. In a cross section from near American University southeast along Massachusetts Avenue the plateau descends from about 370 to 330 feet, which is less steep than the slope on Wisconsin Avenue.

The Tenleytown plateau remnant followed by Wisconsin Avenue is capped by about 12 to 20 feet of red loam gravel of typical Brandywine [Bryn Mawr] in places highly ferruginous. This is underlain in greater part, if not throughout, by a sheet of fine buff sand believed to be weathered Calvert. There is 30 or 40 feet of this sand at places, but locally it is much thinner. To the north it lies on rotted gneiss, but to the south there is an outlying wedge of Potomac arkose and gravel of that formation that may be 40 feet thick at most. This (Potomac) wedge thins out by truncation near Idaho Avenue.

There is an outlier of the Brandywine-capped plateau on Foxhall Road, a short distance south of Wesley Heights, the top of which is at an altitude of 350 feet. It consists of a thin remnant of fine brown loamy sand (Calvert?) underlain by a thin wedge of Potomac arkose; the latter lies on gneiss. These high plateau remnants end eastward in a sharp descent 100 feet or more into the old trough of the river with its gravel cap of river-terrace deposits.

Virginia.—Several remnants of the high plateau remain as flat-topped ridges in northern Virginia west and southwest of Washington. They are capped by the characteristic red loam Brandywine gravel, lying mostly on rotted gneiss but in small part on thin remnants of red loam of supposed Calvert formation,[5] and to the east there are also thin outlying wedges of gravel underlain by arkose of the basal formation of the Potomac group. The smooth gravelly surface typical of the plateau slopes up from 375 feet on the east to 506 feet in Gantt Hill and 493 feet in Freedom Hill, in accord with the general slope of the Brandywine high plateau east of the Potomac and Anacostia rivers. The gravel cap presents sharp edges above adjoining slopes with some gravel talus on slopes of rotted gneiss below. To the east it drops rapidly to the river terraces in Washington. At

[5] These and similar deposits in the District of Columbia are probably residual from sericite schist. C. W. Cooke

the western margin of the large areas west of Falls Church it has a long erosion slope into much lower land, and the elevation of the country for many miles is below 500 feet. Near the western edge of these outliers the Brandywine [Bryn Mawr] gravel is underlain by small wedges of Calvert formation, a rather bright yellow-brown sandy loam typical of weathered Calvert sandy clay in other places. In a quarry for road metal half a mile west-southwest of Tyson cross roads this loam is well exposed under the Brandywine gravel, 10 feet thick and lying on rotted gneiss. The lowest beds here contain alternating thin beds of gravel, and in a clay layer a few feet above one of these gravel layers fragmentary shell impressions which suggest *Lucinas* of the Calvert formation were observed by Darton. Other exposures of this material were noted north and east of Tyson cross roads, half a mile west of Wedderburn station and just south of the old trolley line a mile west of West Falls Church station.

In Halls Hill, a mile west of Cherrydale, the cap of Brandywine gravel is at an altitude of 420 feet. It lies on Potomac arkose and gravel to the east with a small thin intervening wedge of supposed Calvert yellow loam on the southeast slope at 370 feet. The small outliers of Brandywine gravel south and southeast of East Falls Church are near an altitude of 400 feet and lie on rotted gneiss. The Brandywine gravel cap at Munson Hill has an altitude of 380 feet. It surmounts a long slope descending to the wide river terrace at Bailey cross road.

The plateau outliers east and southeast of Annandale are at altitudes of 400 feet or more, and in most of this area the Brandywine gravel is underlain by thin remnants of gravel and arkose apparently of Potomac age.

Overlap Relations in Eastern Virginia

Most of the western margin of the younger Coastal Plain deposits from Rappahannock River to James River was re-examined by me in 1911 and 1932, and, while the history indicated is the same as in Maryland, local details of overlap are different. The Potomac group lies on the granite and gneiss at altitudes which diminish gradually south of the Rappahannock River, and the Calvert beds overlap to a greater extent beyond the western edge of the Potomac as well as of the Eocene. The high plateau also extends more widely west onto the Piedmont zone. As explained above, the Marlboro clay member of the Nanjemoy formation extends far south into Virginia as a well-marked unit in the Coastal Plain succession, but to the west it is truncated and overlapped by the Calvert beds. This truncation was effected at the beginning of or just before Calvert time, and it bevelled strata from upper Nanjemoy to Potomac. The upper formations of the Potomac group may have extended farther west originally and been removed in late Cretaceous or early Tertiary time.

South from Fredericksburg the overlap relations of the western margin of the various Coastal Plain deposits remain uniform, except that near Doswell (Hanover Junction) a mound of red Triassic (Newark) strata is present. The Potomac beds continue far south with their western edge overlapped irregularly by Eocene and Miocene deposits. For many miles the Miocene deposits overlap westward onto granite, and the gravel of the Plain overlaps still farther west, a relation which exists far beyond Richmond. As shown by characteristic outcrops on Shockoe, Gillie, and Almond creeks, and the east branch of James River to and beyond Dutch Gap canal, the western edge of the lower part of the Potomac group lies on the irregular upsloping surface of granite. The same condition exists on Appomattox River and in Sussex County. A protruding knob of granite crops out in James River a mile north-northwest of Dutch Gap canal. I determined these relations long ago, as set forth in my map in Fontaine's *Potomac formation in Virginia* (1896) and my *Geology of Richmond and vicinity* (1911, Pl. 2, sec. 8).

The Eocene deposits are conspicuous along the marginal outcrops of the Coastal Plain succession from Fredericksburg southward, but the Marlboro clay is overlapped at most places; the only outcrop observed was on the right bank of James River 2 miles below City Point (Clark and others, 1912) where 5 feet of it appears. Clark also mentions 4 feet of mottled clay, at Coggins Point 5 miles below City Point,

but apparently this is at or near the top of the Nanjemoy formation.

It is evident that from the early Cretaceous to late Tertiary north to south shore lines persisted or rather recurred near a zone passing through Richmond. Doubtless, however, deposition extended to sea margins much farther west than the present limits of the formations and were truncated in a narrow zone of increased uplift down to early Pleistocene time. As will be shown later, the "Fall line" is in this zone of increased uplift, and no definite continuous fault is present.

Deformation of the Lafayette Plain

Out on the central part of the Coastal Plain the plateau surface is a wide plain with general rise to the west and northwest at a low rate but with notable increase in rate in the "Fall line" zone. Its smooth slope in the region to the east is interrupted by low undulations, with notable rise onto the divides and considerable slope toward the larger valleys, features which were mistaken by Dryden in 1938 for structure; actually they simply show that the (Brandywine) gravel sheet was laid on a surface on which the larger drainage was outlined and eroded to some extent. The 50-foot contour lines in Plate 4 show these features, but of course these lines are only approximate where the remnants have to be connected by broken lines.

South of Fredericksburg to far beyond Richmond the rate of upslope of the Coastal Plain deposits overlapping the Piedmont zone is moderate.

The increase of upslope of the remnants of the high plateau about Washington is well shown by the fact that the edge of the plateau, with an altitude of 310 feet on Good Hope Hill, 320 feet at Soldiers Home, 352 feet near Silver Spring, rises on Wisconsin Avenue ridge from 350 feet at Mount Alto Hospital to 420 feet at Reno, near Tenley, D. C. To the east is the broad erosion area covered by river terraces.

Unfortunately the structure in the eroded area now occupied by the older parts of Washington, Alexandria, and Hyattsville can only be surmised, for in them the Calvert formation has been widely trenched. Presumably there was here some sag of the north-south surface of the Brandywine plain at an early stage of the excavation of the wide trench of the Potomac River and its Northwest Branch. At Patuxent River the flattening to the southeast out on the Coastal Plain area is a marked feature, giving place to a steeper upturn along the "Fall line" zone. In the outlier at Catonsville west of Baltimore an altitude of 540 feet is attained, apparently by a sharp rise. This is west of a line passing near the center of Baltimore, and it continues across the valley of Gunpowder Falls to the highlands beyond Susquehanna River where one of the outliers of the high plateau attains an altitude of 468 feet.

South of Washington this steepened uplift in the "Fall line" zone shows a rise from 363 feet in the remnant just west of Cherrydale to the jump-off west from 506 feet, just west of Vienna (Freedom Hill and Gantt Hill). In Fairfax County, Virginia, south of the Southern Railroad, the highest gravel outliers are at an altitude of 230 feet, but these are much lower than the Brandywine [Bryn Mawr] and are surely river terraces. A gravel-covered plateau remnant at 303 feet about 2 miles west of Lawton Station and 2 miles north of Occoquan, however, is believed to be Brandywine. Other high plateau remnants occur south of Occoquan at about the same altitude, and another is the divide south of Quantico Creek 5 miles northwest of Dumfries at 385 feet. These isolated summit caps descend to an altitude of 200 feet near Cherry Hill, a rather steep decline. The ridge just west of Quantico has several outliers, from one at 300 feet 3 miles west of Triangle to another at 242 feet 2 miles west of Quantico. On the divide between Chopawamsic Creek and the north branches of Aquia Creek, caps of gravel (supposed Brandywine) occur up to 353 feet. On ridges on both sides of Potomac Creek valley southward from Stafford, many such gravel remnants occur at altitudes above 300 feet, sloping down to less than 200 feet near Longitude 77° 20′.

In ridges north of Fredericksburg, high plateau remnants slope up to an altitude of nearly 300 feet, rather steeply at first with the rise to 200 feet a short way east of Falmouth. East of

there a very low undulating decline to an altitude of about 150 feet extends far out on the long ridge between the Potomac and Rappahannock rivers. Farther south the high plain has a general slight slope to the southeast with distinct troughs forming the larger valleys. The rise to the west is at a rate close to that of the west margin of the Coastal Plain surface which blends to the west into the low upslope of the Piedmont area. The deposit of Brandywine sand and gravel thins out to a feather edge on the west; no careful survey was made of this feature. The position of the original margin to the west cannot be suggested.

South of the latitude of Fredericksburg the (Brandywine) high plateau has the same characteristic flatness with low declivity toward the southeast that it has in southern Maryland. The divides between rivers are low ridges declining in height to the southeast and sloping laterally into the larger valleys 50 feet or more; however, in the larger valleys where the gravel deposit is stripped off, the total original declivity laterally cannot be ascertained. The rate of downslope to the southeast along the crests of the broader divides averages about 50 feet in 8 miles.

Near the longitude of Richmond the upslope of the western margin of the high-plain gravel deposit increases but at a less rapid rate than in the country north of Fredericksburg. In the western part of Richmond and its western suburbs the altitude rises from 180 to 260 feet, but near Ashland the rate is lower. However, all along the western margin of the deposit the rise is much steeper than it is in the wide zone of interstream divides to the east. In the city of Richmond the high plateau is notably flat. It is clear that in the "Fall line" zone there is a distinct increase in rate of upslope which I believe was caused by uplift. In the continuation of the planation farther west across the bare gneiss the rise of the land is at a low rate.

Bedrock Surface

For many years I have been obtaining data as to the position of the bedrock surface under the Potomac formation in eastern Maryland and Virginia and late in 1947 wrote an account of its position in the Washington region. The relations in the Baltimore region are shown in maps published by the Maryland Geological Survey. As stated above the idea that the floor is uplifted abruptly several hundred feet by the "Fall line fault" is erroneous, for no such extended fault exists. The bedrock which constitutes the surface west of Washington and Baltimore slopes to the east at a nearly uniform rate of about 100 feet to the mile. The surface of this floor is irregular in places due to pre-Potomac erosion, and there are a few small faults. Deep holes found that the floor descends to more than 1200 feet below sea level a few miles east of the Washington and Baltimore region.

River-Terrace Deposits

The city of Washington and other cities along the Fall Line are built largely on terraces cut by various dominant rivers which made wide trenches like broad steps in the Brandywine plain. This cutting occurred in Quaternary time, which included in its earlier part an epoch when glaciers extended into Pennsylvania and New Jersey. Vertical uplift amounted to about 400 feet on the longitude of Washington but was considerably less to the east and south. Valley trenching progressed irregularly and finally cut to below sea level. Thus the general topography around Washington has resulted from this trenching of the Brandywine plain, which has an altitude of more than 500 feet west of Falls Church, 423 feet at Tenleytown in the western part of Georgetown, and 300 feet in the plateau edge east of Anacostia River. At Washington erosion developed a great embayment in the old plateau, in which is a succession of extensive river terraces capped by gravel, sand, and loam, such as those on which stand the Capitol and the White House. These prominent terraces surmount long downslopes to the tide marsh on the south, and now all the larger rivers are deep tidal estuaries.

The outer or first-made terrace trench in the plateau has a steep sloping descent to the first terrace, such as is found in the east descent from Munson Hill with its remnant of Brandywine formation at 323 feet down to the river terrace at Baileys cross roads at 254 feet. This feature is shown in cross section (Fig. 9) where

the descent is about 70 feet and is all gneiss. The river terrace at the cross roads is covered with deposits of sand and gravel much younger looking than most of the gravel on the high plateau, and it has a very smooth surface sloping gently east.

FIGURE 9.—SECTION OF BRANDYWINE [Bryn Mawr] OUTLIERS EAST OF FALLS CHURCH SOUTHEASTWARD TO BAILEYS CROSS ROAD [The lower terrace is now classified as Brandywine.]

Showing relations to river-terrace deposits at Crossroads.

Several wide river terraces along the Potomac valley form wide steps down to the alluvial flats bordering the river. The lowest excavation cuts to considerably below sea level in a narrow trench which has been flooded by tide water as far as the western part of Georgetown. A similar condition exists on the Rappahannock River as far as Fredericksburg, and on the other larger rivers of the Coastal Plain.

I believe that the trenching and the development of terraces was done by streams of about the size of the present rivers, which shifted their courses. As these shifting streams cut deeper and deeper, their gravel-covered beds remained as wide terrace plains which were elevated as uplift continued. The rivers were never wider than now, but their declivity was maintained sufficiently steep for the transportation of coarse gravel and boulders which nearly everywhere constitute the terraces.

Terrace formation could not have been simultaneous at uniform levels all the way across the valley for the swift-flowing streams had banks only a few rods apart. Terraces developed at various heights and at different places as the streams shifted their courses. The river deposits developed first on one side of the narrow valley and then widened as the outer bank was removed. As uplift progressed and wide flat bottoms were developed they were covered by materials brought by the streams. Deposition of the river deposits at all stages was of course largely adjacent to the stream, but the shifting course of the streams resulted in a smooth mantle of wide extent left as a terrace when the stream developed the next deeper trench. Such is the terrace which extends from Baileys cross roads continuously to the heights just south and west of Alexandria. There were many similar terrace plains at various elevations.

The lowest bench in these valleys is alluvium, mostly of fine-grained material. The distribution of the river gravel and also of alluvium is shown in various detailed maps; the deposits near Washington are presented on the author's map of the Sedimentary Formations, issued by the U. S. Geological Survey in 1947. The intricate details of distribution could not be shown in Plate 1 of this present paper, because of the small scale of the map.

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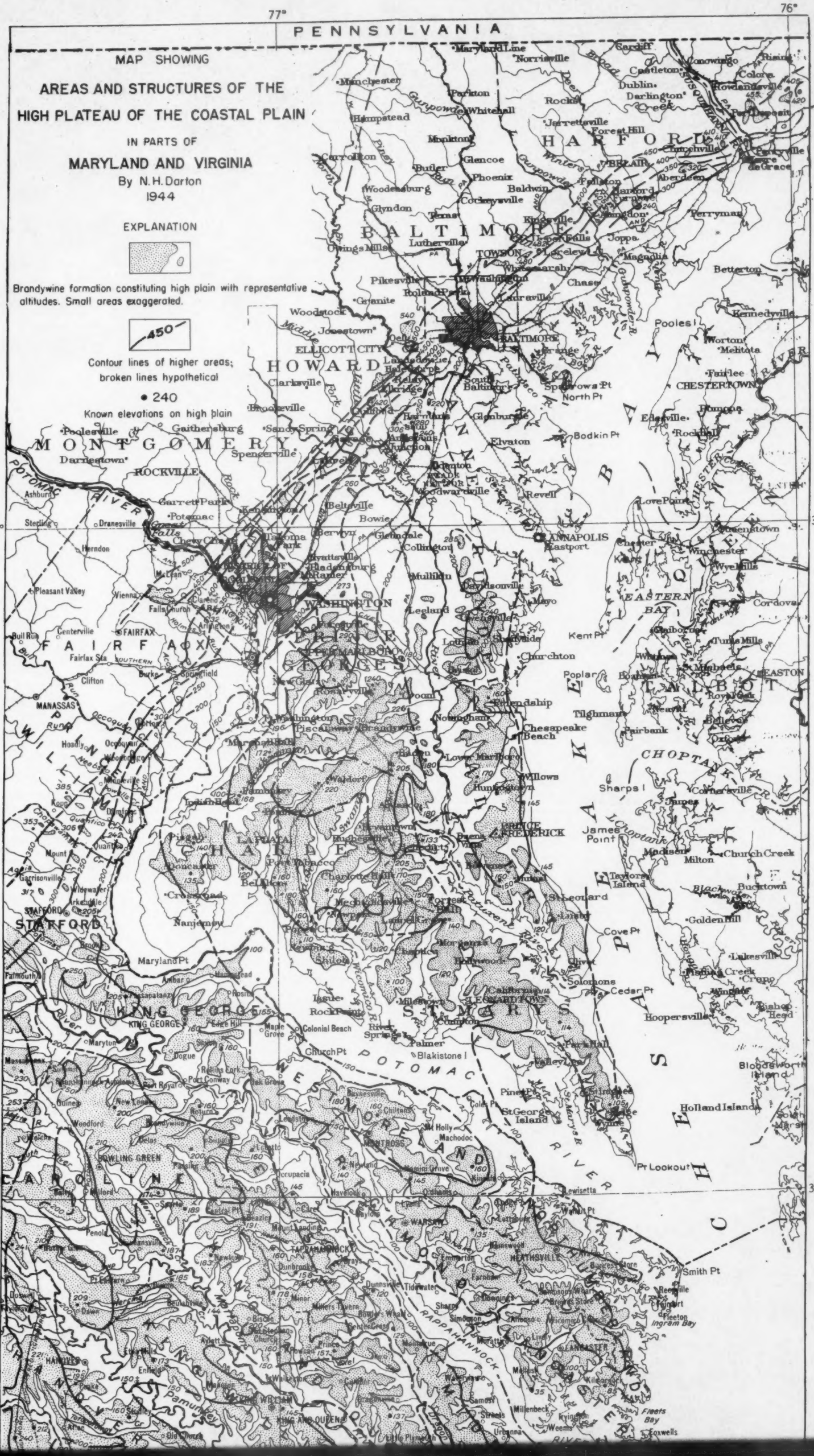
77°
76°
PENNSYLVANIA
MAP SHOWING
AREAS AND STRUCTURES OF THE
HIGH PLATEAU OF THE COASTAL PLAIN
IN PARTS OF
MARYLAND AND VIRGINIA
By N. H. Darton
1944
EXPLANATION
Brandywine formation constituting high plain with representative altitudes. Small areas exaggerated.
450
Contour lines of higher areas; broken lines hypothetical
• 240
Known elevations on high plain
39°
38°
BALTIMORE
HARFORD
HOWARD
MONTGOMERY
PRINCE GEORGES
ANNE ARUNDEL
CALVERT
CHARLES
ST MARYS
KING GEORGE
STAFFORD
FAIRFAX
PRINCE WILLIAM
CAROLINE
KING AND QUEEN
KING WILLIAM
ESSEX
LANCASTER
NORTHUMBERLAND
WESTMORELAND
RICHMOND
TALBOT
QUEEN ANNES
KENT
CHESTERTOWN
EASTON
ANNAPOLIS
WASHINGTON
BALTIMORE
ELLICOTT CITY
ROCKVILLE
LA PLATA
LEONARDTOWN
TOWSON
POTOMAC RIVER
PATUXENT RIVER
RAPPAHANNOCK RIVER
CHESAPEAKE BAY
EASTERN BAY
CHOPTANK R.
MIDDLE R.
GUNPOWDER R.
BIG GUNPOWDER R.
PATAPSCO R.
SASSAFRAS R.
BIG ELK CREEK
NORTH EAST R.
ELK R.
SOUTH R.
SEVERN R.
WEST RIVER
ROCK CREEK
ANACOSTIA R.
POTOMAC RIVER
ST MARYS R.
WICOMICO R.
PAMUNKEY R.
MATTAPONI R.
YORK R.
Maryland Line
Norrisville
Manchester
Parkton
Hampstead
Whitehall
Monkton
Glencoe
Phoenix
Baldwin
Cockeysville
Glyndon
Texas
Kingsville
Fullerton
Perryman
Joppa
Magnolia
Betterton
Carroll Ton
Butler
Woodensburg
Owings Mills
Lutherville
Towson
Pikesville
Granite
Woodstock
Jessestown
Oella
Relay
Elkridge
Laurel
Chase
Rockhall
Edgewood
Aberdeen
Havre de Grace
Perryville
Port Deposit
Conowingo
Colora
Rowlandsville
Castleton
Dublin
Darlington
Jarrettsville
Forest Hill
Churchville
Bel Air
Fallston
Harford
Kennedyville
Worton
Melitota
Fairlee
Chestertown
Rock Hall
Edesville
Bodkin Pt
North Pt
Sparrows Pt
Glenburnie
Elvaton
Clarksville
Brookeville
Poolesville
Gaithersburg
Sandy Spring
Spencerville
Darnestown
Ashburn
Sterling
Dranesville
Herndon
Pleasant Valley
Vienna
Falls Church
Centerville
Bull Run
Fairfax Sta.
Clifton
Manassas
Occoquan
Woodbridge
Dumfries
Quantico
Stafford
Garrisonville
Arkendale
Aquia
Mount Pleasant
Doncaster
Cross Road
Nanjemoy
Maryland Pt
Hague
Ambar
Rosita
Rappahannock
Massaponax
Fredericksburg
Belvidere
Port Tobacco
Charlotte Hall
Mechanicsville
New Port
Piney Point
Shiloh
Issue
Rock Point
Milestown
Compton
Colonial Beach
Maple Grove
Spring Field
Palmer
Blakistone I.
Church Pt
Dogue
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King George
Port Conway
Port Royal
Oak Grove
Bayneville
Chilton
Pinet Pt
St George Island
Holland Islands
Bloodsworth Island
Pt Lookout
Lewisetta
Smith Pt
Reedville
Fleeton
Ingram Bay
Fleets Bay
Foxwells
Millenbeck
Kilmarnock
Irvington
Weems
Urbanna
Mollusk
Lancaster
Heathsville
Mainswood
Burgess Store
Emmerton
Farnham
Tidewater
Dunnsville
Rappahannock
Warsaw
Lottsburg
Mount Landing
Tappahannock
Dunbrooke
Penola
Hanoverton
Newtown
Beulahville
Dawn
Hanover
Ashland
Atlee
Enfield
Pamunkey
Studley
Old Church
Little Plymouth
Prince Frederick
Huntingtown
Willows
Sharps I.
James Point
Taylors Island
Madison
Milton
Church Creek
Buckstown
Golden Hill
Cove Pt
Solomons
Cedar Pt
Hoopersville
Lakesville
Crane
Bishop Head
Parks Hall
Valley Lee
Mechodoc
Machodoc
Montross
Oak Hall
Newland
Maxima Grove
Kinsale
Orchards
Bowlers Wharf
Mollusk
Sharps
Simonson
Allesco
Wicomico
Livery
Mattox
Samosa
Streets
Millenbeck
Kilmarnock
Irvington
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Conowingo
Rising Sun
Colora
Rowlandsville
Castleton
Dublin
Darlington
Jarrettsville
Forest Hill
Churchville
Bel Air
Fallston
Aberdeen
Havre de Grace
Perryville
Port Deposit
Perryman
Betterton
Kennedyville
Worton
Melitota
Fairlee
Chestertown
Rock Hall
Edesville
Bodkin Pt
North Pt
Sparrows Pt
Glenburnie
Elvaton
Clarksville
Brookeville
Poolesville
Gaithersburg
Sandy Spring
Spencerville
Darnestown
Ashburn
Sterling
Dranesville
Herndon
Pleasant Valley
Vienna
Falls Church
Centerville
Bull Run
Fairfax Sta.
Clifton
Manassas
Occoquan
Woodbridge
Dumfries
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Garrisonville
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Hague
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Irvington
Weems
Urbanna
Mollusk
Lancaster
Heathsville
Mainswood
Burgess Store
Emmerton
Farnham
Tidewater
Dunnsville
Rappahannock
Warsaw
Lottsburg
Mount Landing
Tappahannock
Dunbrooke
Penola
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Ashland
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Pamunkey
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Tappahannock
Dunbrooke
Penola
Hanoverton
Newtown
Beulahville
Dawn
Hanover
Ashland
Atlee
Enfield
Pamunkey
Studley
Old Church
Little Plymouth

1944

EXPLANATION

Brandywine formation constituting high plain with representative altitudes. Small areas exaggerated.

Contour lines of higher areas; broken lines hypothetical

• 240

Known elevations on high plain

BALTIMORE
HOWARD
MONTGOMERY
FREDERICK
CARROLL
FAIRFAX
PRINCE GEORGES
ANNE ARUNDEL
CALVERT
CHARLES
KING GEORGE
STAFFORD
WESTMORELAND
NORTHUMBERLAND
LANCASTER
RICHMOND
ESSEX
KING AND QUEEN
KING WILLIAM
NEW KENT
TALBOT
CAROLINE
QUEEN ANNES
KENT
CAECIL
DORCHESTER
SOMERSET
WICOMICO
WORCESTER
ACCOMACK
NORTHAMPTON

Chesapeake Bay
Eastern Bay
Choptank River
Patuxent River
Potomac River
Rappahannock River
Pocomoke River
Nanticoke River
Wicomico River
Severn River
Magothy River
Middle River
Gunpowder River
Back River
Patapsco River
Bush River
Sassafras River
Elk River
Northeast River
Chester River
Corsica River
Wye River
Miles River
Tred Avon River
Little Choptank River
Fishing Bay
Tangier Sound
Pocomoke Sound
Manokin River
Big Annemessex River
Little Annemessex River
Monie Bay
Broad Creek
Back Creek
Deep Creek
Harris Creek
Dividing Creek
Kedges Straits
Hooper Strait
Honga River
Fishing Creek
Slaughter Creek
Little Choptank River
Broad Creek
Cabin Creek
Parsons Creek
Taylors Island
Hoopers Island
Holland Island
Bloodsworth Island
Smith Island
Tangier Island
Watts Island
Janes Island
Deal Island
Great Fork
Little Fork
Big Fork
Rhodes Point
Crisfield
Somers Cove
Marumsco Creek
Occoquan Creek
Neabsco Creek
Quantico Creek
Chopawamsic Creek
Aquia Creek
Potomac Creek
Accokeek Creek
Mattawoman Creek
Piscataway Creek
Zekiah Swamp
Wicomico River
Port Tobacco River
Mattox Creek
Nomini Creek
Yeocomico River
Coan River
Little Wicomico River
Great Wicomico River
Cockrell Creek
Curtis Creek
Bodkin Creek
Rock Creek
Herring Creek
Whitehall Creek
Weems Creek
Back Creek
Mill Creek
Spa Creek
Severn Run
Meredith Creek
Broad Creek
Bacon Ridge Branch
Cabin Branch
Herring Bay
Rockhold Creek
Deep Creek
Lake Waterford
Lake Fairfax
Lake Audubon
Lake Barcroft
Lake Accotink
Lake Manassas
Lake Ridge
Lake Montebello
Lake Roland
Lake Clifton
Lake Evergreen
Lake Montebello
Lake Elkhorn
Lake Kittamaqundi
Lake Elkhorn
Lake Prince William
Lake Jackson
Lake Montebello
Lake Roland
Lake Clifton
Lake Evergreen
Lake Montebello
Lake Elkhorn
Lake Kittamaqundi
Lake Elkhorn
Lake Prince William
Lake Jackson

Glyndon, Cockeysville, Texas, Kingsville, Lutherville, Joppa, Towson, Perryman, Magnolia, Betterton, Owings Mills, Pikesville, Woodstock, Granite, Jonestown, Oella, Ellicott City, Relay, Elkridge, Clarksville, Brooklyn Park, Baltimore, Arbutus, Halethorpe, Lansdowne, Catonsville, Arlington, Brooklandville, Glyndon, Glenburnie, Sparrows Pt, North Pt, Edgemere, Dundalk, Pooles I, Worton, Melitota, Fairlee, Kennedyville, Chestertown, Rock Hall, Eastern Neck, Eastern Neck I, Bodkin Pt, Elvaton, Glenburnie, Gaithersburg, Sandy Spring, Spencerville, Olney, Brookeville, Poolesville, Darnestown, Rockville, Garrett Park, Kensington, Potomac, Bethesda, Chevy Chase, Takoma Park, Silver Spring, Wheaton, Glenmont, Aspen Hill, Norbeck, Layhill, Olney, Ashburn, Sterling, Dranesville, Great Falls, Herndon, Pleasant Valley, Vienna, Falls Church, Arlington, Alexandria, Washington, Mt Rainier, Hyattsville, Bladensburg, Berwyn, Beltsville, Bowie, Glenndale, Collington, Mullikin, Davidsonville, Mayo, Revell, Love Point, Queenstown, Winchester, Wye Mills, Cordova, Easton, Oxford, Royal Oak, Tunis Mills, Claiborne, Kent Pt, Eastport, Annapolis, Chester, Kent, Centerville, Fairfax, Bull Run, Fairfax Sta, Clifton, Burke, Springfield, Manassas, Occoquan, Woodbridge, Dumfries, Quantico, Hoadly, Independent Hill, Haymarket, Gainesville, Buckland, Warrenton, Waterloo, Sperryville, Flint Hill, Front Royal, Linden, Marshall, Rectortown, Upperville, Paris, Ashby Gap, Millwood, Berryville, Boyce, Clarke, Winchester, Stephens City, Middletown, Strasburg, Woodstock, Edinburg, Mount Jackson, New Market, Timberville, Broadway, Harrisonburg, Dayton, Bridgewater, Mount Crawford, Port Republic, Grottoes, Elkton, Stanley, Luray, Shenandoah, Page, Rockingham, Penn Laird, Mount Solon, Staunton, Verona, Fishersville, Waynesboro, Crimora, Greenville, Basic City, Afton, Rockfish, Nellysford, Wintergreen, Roseland, Arrington, Lovingston, Shipman, Piney River, Tyro, Massies Mill, Amherst, Madison Heights, Lynchburg, Forest, Bedford, Big Island, Thaxton, Goodview, Moneta, Hardy, Rocky Mount, Boones Mill, Callaway, Ferrum, Penhook, Gretna, Chatham, Brosville, Danville, Blairs, Dry Fork, Stokes, Ringgold, Hurt, Keeling, Gretna, Halifax, South Boston, Clarksville, Bracey, Boydton, Lawrenceville, Alberta, Dolphin, Warfield, Emporia, Skippers, Wakefield, Sedley, Waverly, Disputanta, Petersburg, Hopewell, Prince George, Ettrick, Chesterfield, Richmond, Midlothian, Manchester, Bon Air, Clover Hill, Matoaca, Chester, Colonial Heights, Ware Neck, Saluda, Gloucester Point, Yorktown, Grafton, Seaford, Tabb, Poquoson, Hampton, Newport News, Phoebus, Fort Monroe, Buckroe Beach, Bethel, Big Bethel, Hampton, Elizabeth City, Fox Hill, Norfolk, Portsmouth, Suffolk, Chuckatuck, Driver, Berkley, Deep Creek, Pinners Point, Churchland, Saxis, Onancock, Onley, Parksley, Nassawadox, Cape Charles, Cheriton, Exmore, Willis Wharf, Accomac, Wachapreague, Chincoteague, Oak Hall, Melfa, Eastville, Cape Charles, Kiptopeke, Cape Henry, Virginia Beach, Pungo, Princess Anne, Kempsville, Creeds, Oceana, Dam Neck, Pungo, Blackwater, Bucktown, Golden Hill, Lakesville, Pleasant Grove, Creeds, Wingate, Cedar Pt, Solomons, Cove Pt, Olivet, Park Hall, Valley Lee, Hooper Island, Hoopersville, Bishop Head, Pt Lookout, Cobb Island, Smith Pt, Reedville, Fleeton, Ingram Bay, Fleets Bay, Windmill Pt, Foxwells, Gwynn, Cherry Pt, Piankatank, Colonial Beach, Maryland Pt, Hague, Montross, Warsaw, Heathsville, Lottsburg, Kilmarnock, Irvington, Lancaster, Weems, Urbanna, Saluda, Gloucester, Mathews, Gwynn, Cherry Pt, Piankatank, Colonial Beach, Maryland Pt, Hague, Montross, Warsaw, Heathsville, Lottsburg, Kilmarnock, Irvington, Lancaster, Weems, Urbanna, Saluda, Gloucester, Mathews

39°
38°
77°
76°

10 0 30 Miles

MAP SHOWING AREAS AND STRUCTURES OF THE HIGH PLATEAU OF THE COASTAL PLAIN

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MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, JULY 6, 1945.

MAP SHOWING

AREAS AND STRUCTURES OF THE HIGH PLATEAU OF THE COASTAL PLAIN

IN PARTS OF

MARYLAND AND VIRGINIA

By N. H. Darton

1944

EXPLANATION

Brandywine formation constituting high plain with representative altitudes. Small areas exaggerated.

450

Contour lines of higher areas; broken lines hypothetical

• 240

Known elevations on high plain

77° 76° 39° 38°

PENNSYLVANIA

MARYLAND LINE

BALTIMORE HARFORD HOWARD MONTGOMERY FREDERICK CARROLL

BALTIMORE ELLICOTT CITY CLARKSVILLE ROCKVILLE GAITHERSBURG DARNESTOWN POOLESVILLE SPENCERVILLE SANDY SPRING BROOKEVILLE WOODSTOCK JOHNSTOWN GRANITE OWINGS MILLS LUTHERVILLE TOWSON PIKESVILLE ROLAND PARK WOODLAWN CATONSVILLE ARBUTUS HALETHORPE RELAY ELKRIDGE SOUTH BALTIMORE SPARROWS PT NORTH PT GLENBURNIE FERRYMAN ARNOLD EDGEWATER ELVATON BODKIN PT WOODWARDVILLE REVELL JULIAN BELTSVILLE BOWIE GLENDALE COLLINGTON ANNAPOLIS EASTPORT MULLIKIN DAVIDSONVILLE MAYO LEELAND CROFTON CHURCHTON LOTHIAN GALESVILLE KENT PT LOVE POINT QUEENSTOWN CHESTER WINCHESTER WYE MILLS CORDOVA EASTERN BAY CHESTERTOWN EDESVILLE ROCKHALL BETTERTON KENNEDYVILLE POOLES WORTON MELITOTA FAIRLEE PERRYMAN JOPPA MAGNOLIA CHASE EDGEWATER BEACH ABERDEEN HAVRE DE GRACE BEL AIR FOREST HILL JARRETTSVILLE DARLINGTON RISING SUN COLORA ROWLANDSVILLE CONOWINGO CASTLETON DUBLIN ROCKS WHITEHALL PARKTON HAMPSTEAD MANCHESTER NORRISVILLE CARSAF

FAIRFAX PRINCE WILLIAM STAFFORD KING GEORGE WESTMORELAND NORTHUMBERLAND RICHMOND CAROLINE ESSEX KING AND QUEEN KING WILLIAM

FAIRFAX CENTERVILLE FAIRFAX STA BURKE SPRINGFIELD CLIFTON MANASSAS BULL RUN OCCOQUAN DUMFRIES QUANTICO GARRISONVILLE MOUNT VERNON ALEXANDRIA ARLINGTON FALLS CHURCH VIENNA HERNDON DRANESVILLE STERLING ASHBURN POTOMAC GREAT FALLS CHEW CHASE GARRETT PARK KENSINGTON PLEASANT VALLEY

PRINCE FREDERICK PRINCE GEORGES CHARLES ST MARYS CALVERT ANNE ARUNDEL TALBOT QUEEN ANNES KENT

PRINCE FREDERICK HUNTINGTOWN WILLOWS SHARPS I LONG CHOPTANK JAMES POINT MADISON MILTON CHURCH CREEK TAYLORS ISLAND BLACKWATER BUCKTOWN ST LEONARD LEARY GOLDEN HILL COVE PT LAKESVILLE FISHING CREEK CREPPO SOLOMONS CEDAR PT HOOPERSVILLE BISHOP HEAD PARK HALL BLOODSWORTH ISLAND HOLLAND ISLANDS SOUTH MARSH PT LOOKOUT LEWISETTA SMITH PT REEDVILLE FLEETON INGRAM BAY FLEETS BAY

LA PLATA PORT TOBACCO CHARLOTTE HALL MECHANICSVILLE NEWPORT PORT CREEK NANJEMOY CROSSROAD DONCASTER PISCATAWAY BRANDYWINE BENEDICT MARYLAND PT ANCHER MASSAPONAX PASSAPATANZY ROSIER ISSUE ROCK POINT MILESTOWN CALIFORNIA LEONARDTOWN COMPTON SPRING PALMER BLAKISTONE I CHURCH PT COLONIAL BEACH MAPLE GROVE KING GEORGE EDGE HILL SHIPPS DOGUE MARYTON RELLIKS FORT PORT CONWAY PORT ROYAL NEW KENT WOODFORD BOWLING GREEN MILFORD PENOLA

WESTMORELAND NORTHUMBERLAND RICHMOND CAROLINE ESSEX KING AND QUEEN KING WILLIAM

POTOMAC RIVER WICOMICO RIVER PATUXENT RIVER PAMUNKEY RIVER MATTAPONI RIVER RAPPAHANNOCK RIVER CHESAPEAKE BAY

WASHINGTON D.C.

ANACOSTIA R. ROCK CREEK PORT TOBACCO R. ZEKIAH SWAMP GUNPOWDER R. BIG GUNPOWDER R. LITTLE GUNPOWDER R. BIG FALLS LITTLE FALLS NORTH BRANCH PATAPSCO R. PATAPSCO R. MIDDLE BRANCH PATAPSCO R. BACK R. GWYNNS FALLS PATUXENT R. PATUXENT RANGE

By N. H. Darton
1944

EXPLANATION

Brandywine formation constituting high plain with representative altitudes. Small areas exaggerated.

450

Contour lines of higher areas; broken lines hypothetical

• 240

Known elevations on high plain

MAP SHOWING AREAS AND STRUCTURES OF THE HIGH PLATEAU OF THE COASTAL PLAIN

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MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, JULY 6, 1945.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 62, PP. 781-796, 6 FIGS. 2 PLS. JULY 1951

PLEISTOCENE VALLEY SEDIMENTS OF THE DUGWAY AREA, UTAH

BY RONALD L. IVES

ABSTRACT

Wartime and post-war drillings and excavations in the Dugway area of Utah exposed a large number of Pleistocene sections from which a rather complete later Pleistocene stratigraphy is derived. These findings confirm and augment those of Gilbert, whose pioneer investigations in the area are gratifyingly thorough and accurate.

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INTRODUCTION

Preliminary Statement

Establishment of Dugway Proving Ground, in south-central Tooele County, Utah, early in 1942, resulted in a large number of drillings and excavations in the lake beds and bajadas forming the floors and inner slopes of the larger valleys. Data obtained from these holes furnishes much information regarding Pleisto-

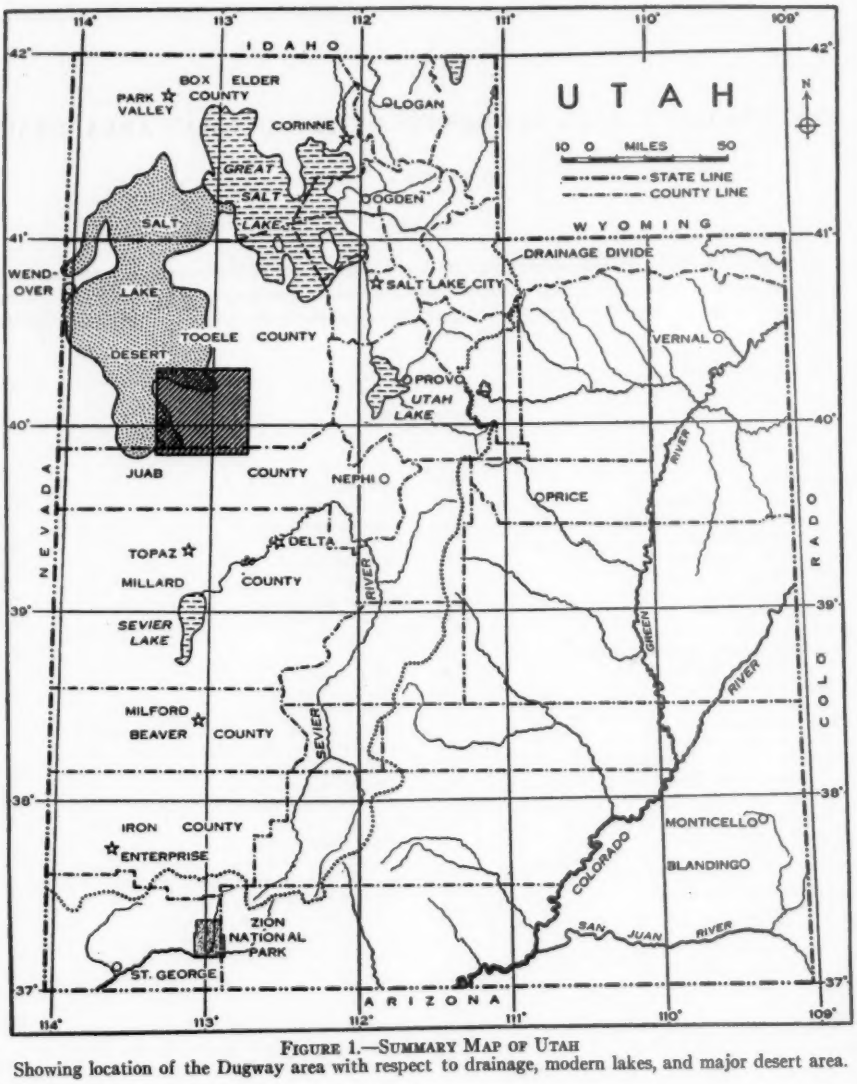

FIGURE 1.—SUMMARY MAP OF UTAH
Showing location of the Dugway area with respect to drainage, modern lakes, and major desert area.

cene stratigraphy of this area, which contains Gilbert's (1890, p. 189–194) "Old River Bed," as well as a large number of interesting, but lesser known, geological phenomena. This paper is based on stratigraphic findings during the period 1942–1947, augmented by information contained in the literature, and some more recently reported findings, largely check data.

Location and Accessibility

The Dugway Area (Fig. 1) is a roughly rectangular stretch of desert, about 30 miles on a side, located where Government Wash and the Dugway Valley merge with the Salt Flats of the Salt Lake Desert in Tooele County, Utah.

The Dugway Area is accessible by paved

military road from Stockton and Tooele, and by improved public road from either Faust or Gold Hill. Many parts of the Dugway Area are, or may be, closed by military regulations, and entry into closed areas is hazardous, due to various tests in progress or to toxic residues from these tests. Information regarding entry is obtainable from Fort Douglas (Salt Lake City, Utah).

Acknowledgments

This study was made possible by Col. John R. Burns, CWS, with the active cooperation of Major A. M. Salisbury, C. E. Aerial reconnaissances of the entire region were made possible by Captain George Langham, AC., assisted by Lt. Christopher Grady, AC.

Valuable field information was given the writer by Mr. Dan T. Orr, pioneer resident of Skull Valley; and climatic information for the area was made available to the writer by Mr. G. K. Greening, of the U. S. Weather Bureau, Salt Lake City, Utah. Discussions of field problems with Dr. S. W. Grinnell, of Division 10, NDRC, and Maj. R. A. Davis, CWS, were most helpful.

Geographical Summary

Preliminary Statement

Major features of the geography of the Dugway Area, as well as of most other parts of the Bonneville Basin, are described competently and correctly in Gilbert's reports (1890; 1928). Smaller features in many locations are also included, with accurate sketches. Parts of the area, of special local interest because of mineral deposits, structure, or fossil content, have been described in some detail by the present writer (Ives, 1946a–n; 1947a–e; 1948a–g; 1949; 1950a–c) with photographs, a method of illustration not readily available to Gilbert.

In a very general way, the Dugway Area consists of two broad desert valleys, Dugway Valley and Government Wash, separated by fault-block ridges on the south and coalescing at the north to join the Salt Flats (Fig. 2; Pl. 3).

Upland Areas

Major upland areas adjacent to Dugway Valley and Government Wash consist of fault-block mountains, trending slightly west of north, with a successive eastward displacement sequence toward the south. In consequence, a crude *en echelon* formation is present, but apparent only in a few places. Although the basin-ranges of this part of Utah are surrounded by desert, parts of them above 6000 feet have a sparse evergreen cover, and some have been glaciated (Blackwelder, 1934; Ives, 1946m). Lower slopes have been deeply incised by the waters of Lake Bonneville, at its various stadia. Great bajadas in many locations, notably in Skull Valley, connect the barren uplands with the broad valley floors.

Valley Floors

From a distance, the valley floors of the Dugway Area appear smooth and level, but closer inspection discloses a rippled, or "washboard" surface (Ives, 1946i) most difficult to traverse in a wheeled vehicle. Sand dunes have accumulated in aerodynamically strategic locations (Fig. 2). Drainage of these valleys is indefinite and changeable, as might be expected from slight gradient and capricious rainfall. Valley floors are spotted with clumps of sage and greasewood, separated by barren clay areas (Pl. 1, fig. 2). Coverage decreases northwestward, about 25 per cent in the southeast, and declines to absolute zero in the salt flats, where many square miles have absolutely no macroscopic vegetation.[1] Connecting the valley floors with the uplands are large bajadas, and numerous alluvial fans and gulch dumps.

Climate and Weather

The Dugway Area, like the rest of the Salt Lake Desert, is arid, with capricious rainfall, hot summers, and cold winters. Mean annual rainfall at Dugway (Fig. 2) is about 5 inches, with a spring maximum. Rainfall variability index exceeds .3.[2] Mean annual temperature at Dugway is about 52°F., mean annual range

[1] Bacteriological assays show a similar condition, air and soil in the salt flats area being more nearly sterile than that in many hospitals.

[2] Computed by dividing the mean rainfall deviation by the mean rainfall. This is a moderately high value, the index for New York City being .125, and that for Yuma, Arizona .446.

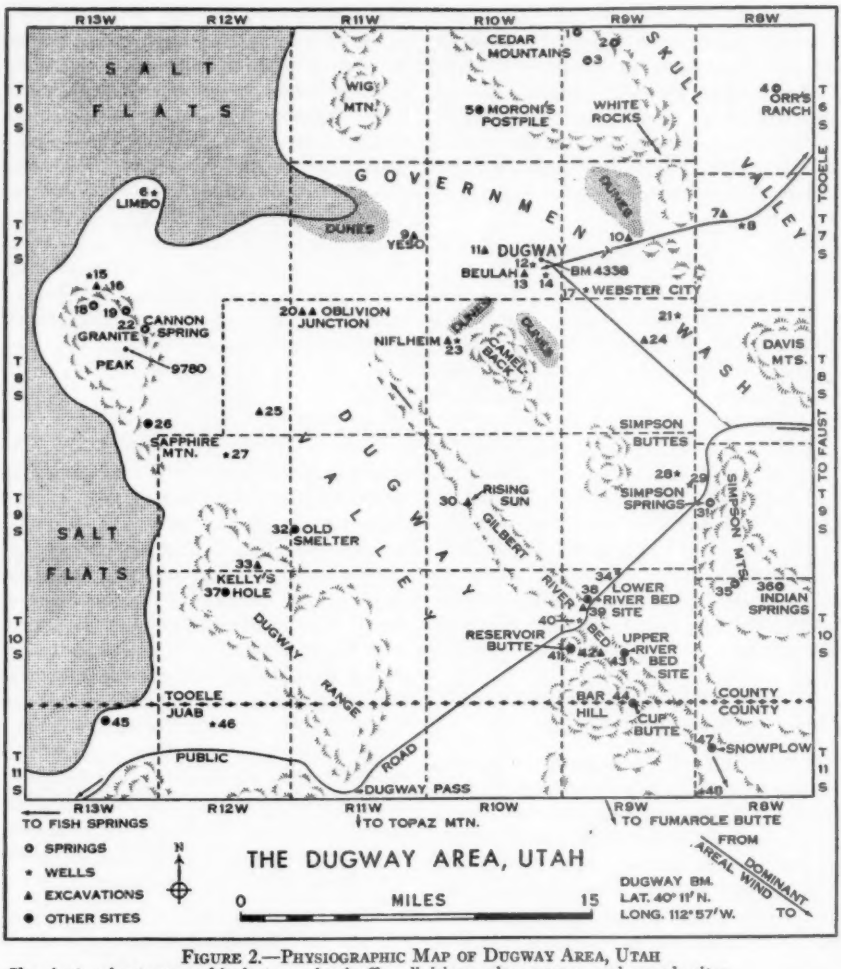

FIGURE 2.—PHYSIOGRAPHIC MAP OF DUGWAY AREA, UTAH
Showing major topographic features, land office divisions, place names, and sample sites.

being 60°F. and extreme range 151°F. (based on 4 years of records). Daily temperature range, as a result of valley air drifts, commonly exceeds 30°F. in summer and is extremely variable within the area because of local terrain effects.

Dominant wind (most mileage) in this area is from the northwest, but is locally modified by valley convections, which produce up-valley winds (anabats) during the day, and down-valley winds (katabats) at night; the wind maximum lags about 2 hours behind the radiational maximum. Mirages and dust devils (Ives, 1947c; 1948d) are common. Specific features of weather, climate, and microclimates of this region have been described elsewhere (USWB 1; Ives, 1950b).

SUMMARY OF PRE-PLEISTOCENE GEOLOGY

Introductory Statement

Fortunately, details of the pre-Pleistocene geology of this region need not be presented for this study, for they are imperfectly known,

and much of the salient evidence, if it still exists, is buried deep beneath lava flows and the valley sediments of present interest.

Gilbert's original study (1890) is still the best overall work on the area, despite obsolescence and lack of photographs. Extensive checking of Gilbert's descriptions against the field evidence discloses a concordance seldom found even in detailed studies. Field investigations in adjacent areas, by Gilbert (1928), Nolan (1935), Calkins and Butler (1943), and Callaghan and Thomas (1939) confirm and amplify Gilbert's findings in those areas, and furnish some basis for extrapolation into, and interpolation across, the Dugway area.

Basal Complex

All hard rock, not readily identifiable as lava flows, within and near the Dugway area is classed as basal complex, for the purposes of this study. This material includes schists and gneisses, most of them multiply intruded (Ives, 1946g; 1946h; 1946n; 1948c), perhaps in Tertiary time; a thick sequence of quartzites and limestones, containing trilobites and classed as early Paleozoic; and a series of red beds, slightly metamorphosed in places, to which a Mesozoic age has been tentatively assigned. Many of these beds are nonfossiliferous, but the presence of loose ammonite and *inoceramis* fragments in the area is suggestive.

East of the area, and in parts of the Cedar Mountains (Fig. 2), the limestones have been locally dolomitized, and the sandstones metamorphosed to quartzites. Sand-filled cavities in some of the limestones indicate the former presence of a karst topography in the area, as do caves in a few locations now completely arid

Volcanics

In and near the Dugway area, volcanic activity was widespread during the Tertiary, and continued sporadically until a very few years ago. Hot springs are still numerous, and those described by Gilbert are still active at the same locations, often with temperatures unchanged since Gilbert's observations (Ives, 1947d; 1948e). Earlier eruptive rocks were rhyolitic; later flows were basaltic. Large volcanic areas near the Dugway area include Fumarole Butte (Gilbert, 1890, p. 332–335) and Moroni's Postpile (Ives, 1946o), a beautifully developed and exposed rhyolite neck, discovered by Dan T. Orr. Large-scale eruptions in this area began in the Tertiary, and continued until mid-Wisconsin time (Gilbert, 1890, p. 319–339). Appreciable quantities of volcanic ash in later Tertiary (Pliocene?) terrestrial deposits and in later Pleistocene lake beds confirm Gilbert's findings.

Valley Sediments

Introductory Statement

Since investigation of the sediments was undertaken in connection with a wartime search for water, much of the information is based on drillers' data. To make possible a generalization of valley floor stratigraphy which bore some relation to that of other areas, well data from the Dugway Area was "tied in" to formations cited by Gilbert, and, where possible, Gilbert's formation names have been used.

Because drilling was stopped either when water was reached or at a depth of 300 feet, most of the sections are "hanging." Well data were augmented, where possible, by studies of excavations and by samplings from explosion craters.

Complexity of the sedimentary sequence, and small areal extent of some formations, makes description by sites preferable to description by formations.

Gilbert's Upper River Bed Site

Gilbert's Upper River Bed Site (Gilbert, 1890, 194–196, Fig. 29, Pl. XXXII), situated where Gilbert's Old River Bed passes between the Simpson Mountains and the McDowell Mountains, at a local drainage divide (Fig. 2, site 43; Pl. 1, fig. 1), was recovered without difficulty from Gilbert's descriptions and maps. Conditions found are in very close accord with those cited by Gilbert, major differences being due to undeniably recent (post-1890) flood deposition and dune migration. Measurements here (Fig. 3) are in close accord with Gilbert's, although a different course, taking full advantage of local gullies, was used. Beds completely exposed at this site are described below.

BLOW SAND: Blow sand here, typical of the entire Dugway area, consists of relatively fine particles of silica, unweathered feldspar, limestone, and salt, with some shell fragments and volcanic ash commonly present. Most of the particles are rounded and show random surface scorings under a microscope. This material is present in dunes, arranged in windrows perpendicular to the course of the local dominant wind (Fig. 2). Although the individual dune particles are extremely mobile, the dunes themselves keep the same positions year after year, even regenerating in a few months if removed (Ives, 1946i).

RECENT WASH: Material here classified as recent wash is the typical gulch dump and outwash fan deposit common to most desert areas. The material consists of unsorted, or poorly sorted, angular fragments of local rocks without any consistent stratification or banding. In the Dugway area, recent wash contains rosettes of tufa at levels below about 5200 feet as a result of erosion of tufa from the Bonneville and other shore lines. Thickness of this material is locally variable. Thickness at the local drainage divide in the Gilbert River Bed, as determined by a test pit, is 3 feet at the estimated point of minimum thickness (Fig. 2, site 42; Fig. 3). Where exposed to winds, surface layer of the recent wash has been stripped of fines, creating a surface layer coarser than the underlying material and somewhat resembling the "desert pavement" of the Gila Valley area.

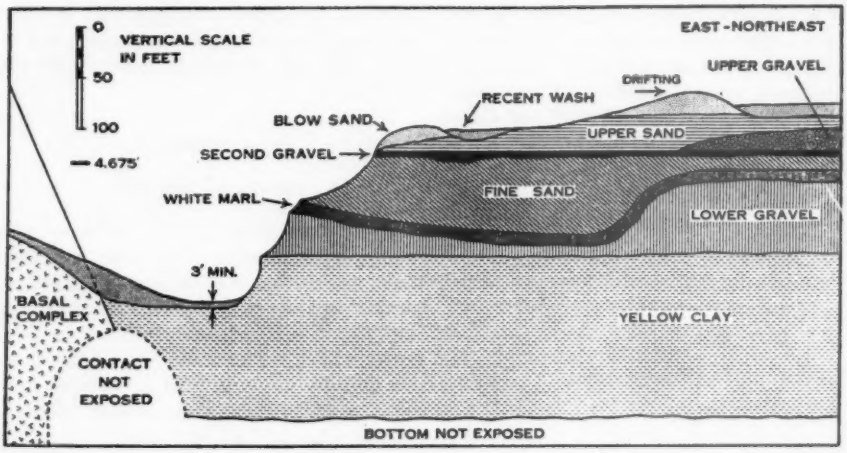

FIGURE 3.—SECTION OF GILBERT'S UPPER RIVER BED SITE

UPPER SAND: Gilbert's Upper Sand (1890, p. 196) is apparently a local deposit of alluvial origin, somewhat modified by wind action. Max-

PLATE 1—GILBERT'S OLD RIVER BED SITES

FIGURE 1. GILBERT'S UPPER RIVER BED SITE

Photographed from the west at the drainage divide in the Gilbert River Bed. Foreground material is recent wash, eroded from Reservoir Butte and Bar Hill (behind camera). Low bluffs forming walls of river bed are composed of yellow clay at base, with lake marls, sands, and gravels above. Top of section, in most locations, is composed of blow sand. Note lava buttes in middle distance; and outwash fan, near center, at base of Simpson Mountains.

FIGURE 2. EAST WALL OF THE GILBERT RIVER BED NEAR GILBERT'S LOWER RIVER BED SITE

Badland forms, carved from the yellow clay, extend about two thirds of the way up the wall, which is here about 130 feet high. White material on floor of River Bed in foregound is relatively recent fill and caliche, having a thickness of about two feet. Volcanic necks in center middle distance have been carved into stacks by waves of the Provo Lake.

FIGURE 1

FIGURE 2

GILBERT'S OLD RIVER BED SITES

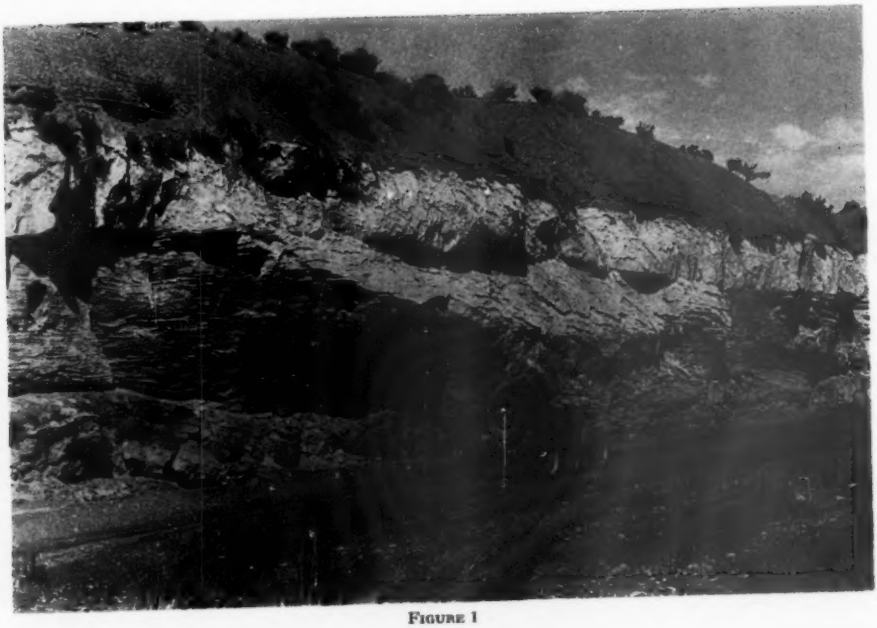

FIGURE 1

FIGURE 2

EXPOSURES OF WHITE MARL

imum observed thickness was about 30 feet, the upper part being so modified by wind action that differentiation between this bed and the blow sand could not be made with any assurance. This sand, like other sands in the area, contains volcanic ash and fine particles of calcite, in addition to silica. Although the bedding of this sand is somewhat indefinite, and may not be original, it appears to be the bottomset beds of a deltaic deposit, perhaps from the drainage of the Indian Springs area (Fig. 2, sites 35, 36).

UPPER GRAVEL: Present, in general, where the upper sand is not, the upper gravel (Gilbert, 1890, p. 196), with a maximum observed thickness of about 4 feet, is apparently a small gulch dump from which the fines have been stripped by wind action. Relation of the upper gravel to the subjacent second gravel is not clear, nor is confident differentiation of the two possible at contacts, as both are similar beds, probably having a common origin and history.

SECOND GRAVEL: Directly beneath the upper sand, and not separated from it by either an angular or erosional unconformity, is Gilbert's (1890, p. 195) second gravel, a mixture of pebbles of local origin and coarse sand, with occasional shell fragments, and a few "niggerheads" of basalt, probably of local origin. Because of undulations of the fine sand, upon which the second gravel is deposited, thickness varies greatly from place to place, with a maximum value of about 5 feet. Gilbert's cited thickness of "about two feet" is a fair average value.

FINE SAND: Beneath the second gravel, and separated from it by a surface of subaerial erosion (in part aeolian), is a bed here called the fine sand (Gilbert's *lower sand*, 1890, p. 195), containing much lime, as well as silica. A few shell fragments, possibly *Lymnaea bonnevillensis*, are now present in the sand, but probably not in their original locations. This material, which blows freely where not protected by an overlying bed, has a variable thickness averaging 25 feet. Lower termination is an intergradation with the subjacent white marl. A part of the variability in thickness of the fine sand is due to the undulations of the white marl, and a part to the "out of phase" undulations of the upper surface.

WHITE MARL: Forming an easily recognizable key bed over much of the Bonneville Basin, the white marl, directly below the fine sand, and having a consistent thickness in this area of about 8 feet, is a laminated marl bed, of intense whiteness. This stratum contains large numbers of beautifully preserved, and unaltered, gastropod shells, principally *Lymnaea bonnevillensis* (Call), and *Amnicola longinqua* (Gould) (Gilbert, 1890, p. 298–299; Ives, 1946e). Counts of the laminae in the white marl, made by extrapolating a detailed count of a small section, suggest 6000 laminae for the marl in most locations. Some of these laminae resemble varves quite closely; some others may not be varves, but groups of layers of undetermined temporal significance. Although the laminae are not of uniform thickness, no periodic changes, possibly representing climatic cycles, were found. Changes in thickness apear to be random, and are not at all consistent along accessible exposures.

The white marl has about the same appearance and characteristics, wherever encountered, but is by no means a level deposit, having been laid down on a surface with more relief than the present desert floor, and covering it much like a coat of paint. Upper termination of the white marl is an intergradation into the fine sand (previously described), sometimes becoming an alternation of deposits, with a layer of sand separating several marl laminae.

LOWER GRAVEL: Immediately below the white marl, separated from it by a parting of considerable relief, is the lower gravel, a bed of assorted sheet-flood deposit of local origin, containing the sweepings of the region, includ-

PLATE 2—EXPOSURES OF WHITE MARL

FIGURE 1—THICK EXPOSURE OF WHITE MARL IN NORTH END OF WHIRLWIND VALLEY

Showing laminated lower portion, massive upper portion, and coarse gravel cover. Jeep in foreground gives approximate scale.

FIGURE 2. BANDED MARL NEAR GRANITE PEAK

Dark bands due to inclusions of mica flakes and black tourmaline of local origin in the regional marl deposit. Note rosette of tufa in upper right (arrow). Cover here is sheetwash, typical of the area.

ing rosettes and fragments of tufa, probably torn from adjacent shoreline deposits. Thickness of this gravel, which has a limited exposure, is extremely variable, with a maximum of perhaps 50 feet. Lower termination of this bed is

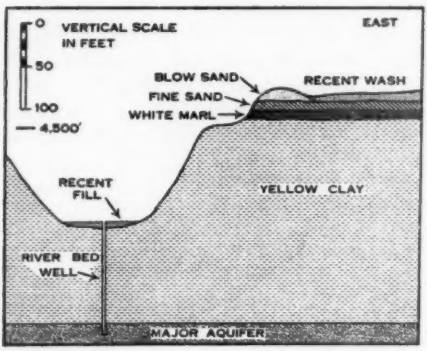

FIGURE 4.—SECTION ACROSS GILBERT'S LOWER RIVER BED SITE

the eroded upper surface of the yellow clay. Differentiation of the lower gravel, second gravel, upper gravel, and recent wash at this site, by any ordinary field method, is possible only because of their position in the stratigraphic column. Where index beds, such as the white marl, are missing and the gravels merge, no distinction can be made.

OTHER BEDS: Below the lower gravel, with its bottom not exposed, is the yellow clay, decribed later, and the basal complex, previously described. Some volcanic structures may be concealed at this site, and downward extrapolation of the channel walls suggests that a wedge-shaped mass of material, characteristics not known, may be present below the yellow clay.

Gilbert's Lower River Bed Site

The lower river bed section, which Gilbert (1890, p. 189–191) regarded as typical, is located on the east side of the Gilbert River Bed (Fig. 2, site 38; Pl. 1, fig. 2), a few yards north of the present road crossing ("Public Road," Fig. 2). A measured section is shown in Figure 4, thickness of the yellow clay being determined from well data (Fig. 2, site 40). At this site, surface material consists of blow sand and recent wash, which rest directly upon the fine sand of the Upper River Bed section. The fine sand intergrades downward into the white marl (Pl. 1, fig. 2), which rests directly on the eroded upper surface of the yellow clay, there being no intervening gravel (lower gravel) here. The white marl of this site can be walked out, with no breaks, to and beyond the Upper River Bed site. Previously undescribed beds pertinent here are:

YELLOW CLAY: The yellow clay is an extensive thick bed of laminated clay, containing much lime, which underlies most of the Bonneville Basin. In this area, it is about 200 feet thick, and may have been as much as 50 feet thicker prior to erosion.

Base of the yellow clay, wherever reached, is a water-bearing boulder and gravel bed, locally called the Major Aquifer, described later. Numerous poorly preserved gastropod shells, of the same species as those in the white marl, are present in the yellow clay, as well as some decalcified bivalves and a few battered diatom skeletons. Most of the shells in the yellow clay disintegrate on drying, whereas those in the white marl, although fragile, are in relatively good condition.

Surface of the yellow clay tends to bleach on exposure and to acquire a coat of caliche, which regenerates when removed. In contrast, clay from some depth is sweet, probably because of slow upward percolation of fresh water from the Major Aquifer. Earthquake and other cracks on the yellow clay "heal" with considerable rapidity, producing minor "faults" in the laminar pattern (Gilbert, 1890, p. 202–213).

Estimates of the number of laminae present in the yellow clay, based on extrapolation from a measured section (site 39, Fig. 2), indicate a maximum count of about 15,000. Although some variations in laminar thicknesses were noted, no convincing evidence of recurrent cycles was noted in the field, and there is no real assurance that these laminae are annual varves.[3]

[3] Leggette and Taylor (1937, p. 110) found about 25,000 varves, by similar methods, in a laminated clay bed almost certainly a northward extension of the yellow clay of this area.

Camelback Section

Logs of several deep wells drilled north and east of Camelback Mountain (Fig. 2, R 10 W, T 8 S), study of numerous excavations in the pertinent here and not previously described, are:—

BENTONITIC CLAY: Forming the surface in the central and lower portion of Government

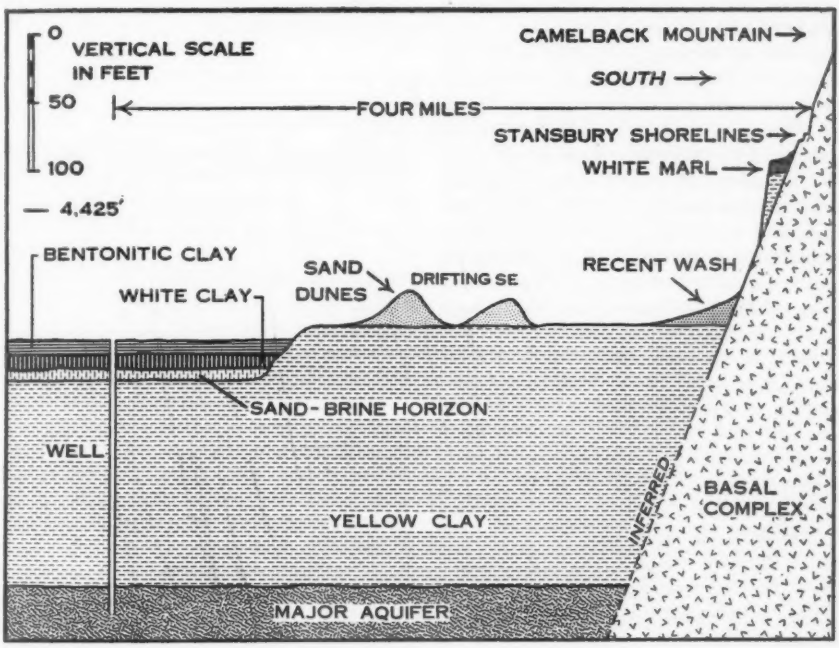

FIGURE 5.—COMPOSITE SECTION OF THE CAMELBACK AREA

general vicinity, and discovery of beds of white marl and yellow clay "hung" on the north side of the mountain, permitted construction of a composite section for the area (Fig. 5). The white marl here shown can be walked out, with a few minor and inconsequential breaks, to the Lower River Bed site. In this area, a new set of sediments, occupying valleys eroded into the yellow clay, is present. Occupying the surface here are the usual blow sand deposits, here forming rather extensive dunes (Fig. 2), which drift slowly to the southeast, in response to the dominant areal wind. Recent wash is present at the bases of the major elevations, usually as fan deposit. About half of the surface in the Dugway area is yellow clay, which supports a scanty growth of sage and greasewood. Beds Wash, and in parts of the Dugway Valley, is a thin laminated nonfossiliferous clay, containing much bentonite. This clay is gray when first exposed, but rapidly bleaches, so that in a few months it becomes indistinguishable from the yellow clay, except for absence of contained shells. Extent of exposure is more than 60 square miles; thickness is from 3 to 12 feet.

This clay, which may be reworked yellow clay mixed with bentonite, contains about 400 laminae, most of which are not very cleraly defined.

WHITE CLAY: Immediately below the bentonitic clay is a bed of intensely white laminated clay, consisting of kaolin, bentonite, and lime, with small amounts of silica and feldspar, but no shells or shell fragments. This material cracks

deeply on drying. Thickness is from 10 to 15 feet. About 1000 laminae are present in this clay at Webster City (Fig. 2, site 17), where it is quite firm. Westward, the clay becomes less firm, and the laminar divisions less distinct. This material resembles a mixture of reworked white marl with bentonite.

SAND-BRINE HORIZON: Directly below the white clay at Dugway (Fig. 2, sites 12, 13, 14), and immediately above the erosion surface of the yellow clay, is a bed of brine-saturated sand, which contains much lime. To this material, the name sand-brine horizon was applied during wartime construction. When the superjacent beds of clay are punctured, brine from this horizon wells upward, carrying with it some sand, and a saline boil spring is created. This commonly plugs itself up in a few weeks, leaving a hummock on the surface.

Base of the sand-brine horizon is determined by the configuration of the underlying yellow clay. Top of the horizon is uniformly at 4310 feet above MSL, and the contact of the sand-brine horizon with the white clay may be conformable. Material contained in this bed is about the same as that in present-day channel sands of this area, except that it lacks the cut-and-fill structure usually found in modern deposits. It is here tentatively classed as a channel sand, pending discovery of more convincing evidence.

YELLOW CLAY: The yellow clay, previously described, underlies the sand-brine horizon, and overlies the Major Aquifer, upon which it rests in probable unconformity.

MAJOR AQUIFER: Immediately below the yellow clay and separated from it by an undulating surface, probably an unconformity, is an extensive, thick, water-bearing bed which is the major aquifer of the region. Water from this aquifer is fresh, potable, and apparently safe for long-term human consumption, despite a high fluorine content. Water in cased wells penetrating this aquifer rises to within about 25 feet of the ground surface, and pumpage at a rate approaching 1,000,000 gallons daily produces a drawdown of only a few feet.

The water-bearing stratum is composed of coarse sand and gravel, with some boulders, all apparently derived from adjacent highlands. Bailed material, from this stratum, when dried, is practically indistinguishable from modern valley-margin alluvium, or from the several gravels of the Upper River Bed site. It seems probable that the Major Aquifer is an ancient subaerial deposit, practically identical with, but of much greater extent than, surface deposits now forming in the area.

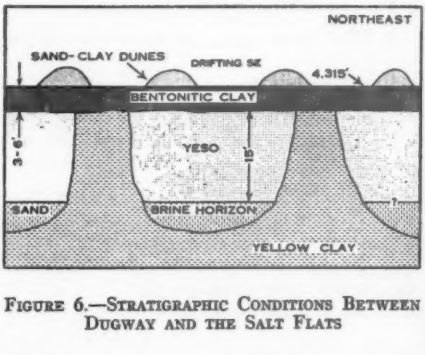

FIGURE 6.—STRATIGRAPHIC CONDITIONS BETWEEN DUGWAY AND THE SALT FLATS

Thickness of the Major Aquifer at Dugway (Fig. 2, sites 12 and 14) and Webster City (Fig. 2, site 17) exceeds 40 feet, bottom of the aquifer not being reached in the several wells at each site.

Yeso Section

Numerous large craters, created during bombing tests on the clay flats in lower Government Wash (Fig. 2, site 9), exposed a partial section differing somewhat from the Camelback Section (Fig. 6). Here, the surface materials and appearance are (or were initially) identical with those at the Camelback site. Beneath the bentonitic clay, however, the white clay is replaced by a material locally known as Yeso.

YESO BEDS: Occupying the same general stratigraphic position as the white clay of the Camelback Site, but located several miles to the west, are the Yeso beds, composed of unstratified lime, gypsum, kaolin, bentonite, and salt, with a consistency varying from that of thick cream to that of putty. This material contracts about 30 per cent on drying.[4] Because

[4] This material, common in the southwest, was first locally identified by PFC Hosteen Yazzie, formerly of Grants, N. M., who stated (correctly) that it is used in place of whitewash by the Pueblo people of that area.

of the tendency of this material to flow under its own weight, craters blown in it fill in within a few hours. In consequence, relation of the Yeso to the subjacent Sand-Brine horizon was not clear. Both the Yeso and the materials of the Sand-Brine horizon occupy channels eroded into the yellow clay at this site (Fig. 6).

Limbo Section

Drilling for industrial water on the edge of the Salt Flats at Limbo (Fig. 2, site 6) produced a section differing considerably from those already described, but of interest in showing the lateral changes in local deposits. Beds encountered in the Limbo Wells are:—

SURFACE SALT: Extending downward from the surface to depths of from a quarter of an inch to more than 20 feet are beds of crystalline salt, mixed with small quantities of gypsum, kaolin, bentonite and lime. These beds, when dry, form incrustations ("lily pads," "salt flowers") where the salt layer is thin, and firm beds of granular salt, able to support heavy vehicles when it is thick. When wet, the salt beds are covered with a skim of saturated brine, containing traces of potash. Surface forms are regenerated annually, and surface damage, such as vehicle tracks and bomb craters, is repaired promptly.

OOZE: Directly below the salt layer, at the Limbo well site, is a thick layer of organic ooze. This, from its color, odor, and texture, was originally classed as fecal matter, but microscopic examination disclosed that it was a mixture of clay and woody material, perhaps algal deposits, in which decay was halted by salinity. Thickness of this ooze is about 4 feet, with the organic components concentrated toward the top. When moistened with fresh water and allowed to "work," this ooze gives off a strong odor of hydrogen sulfide, emitting bubbles of the same gas when submerged.

Beneath the ooze is a clay bed, identical with the yellow clay of the other sections, with a thickness of about 200 feet. Below this is a thin bed of coarse sand, boulders, and gravel, which carries some brackish water, with a high fluorine content. This, with a thickness of about 10 feet, is apparently an extension of the Major Aquifer.

GRAY CLAYS: Immediately below the attenuated Major Aquifer is a series of thinly bedded gray clays, containing sand lenses which carry saturated brine, salt crystals, and occasional small gypsum crystals. Estimates of the number of laminae in these clays, based on measurements of bailed samples, is from 8500 to 43,000. Because these sections may be telescoped by the drill, and because there is no convincing evidence that they are representative samples of the clay beds, these laminar counts may have little evidential value. Thickness of the gray clays is about 100 feet at Limbo Well.

RED CLAYS: Immediately below the gray clays, with a thickness exceeding 40 feet at Limbo Well, is a series of red clays, with lenses of white sand, saturated with brine and potash. Some of the bailings from these clays contained shattered crystals of salt and gypsum.

Other Well Data

Drillings at Granite Peak (Fig. 2, site 15), Niflheim (Fig. 2, site 23), and south of the Snowplow (Fig. 2, site 48), penetrated a bed of gritty red sand, consisting in large part of cemented volcanic ash. This material was also found, naturally exposed, beneath Fumarole Butte (Ives, 1947d), and at White Rocks (T 6 S, R 9 W, Fig. 2). At Granite Peak, this material carried small amounts of foul-smelling hot water.

This red grit is believed to be a pre-Pleistocene deposit of volcanic material, useful only as an indicator of the bottom of the local Pleistocene section.

EXTENT AND SIGNIFICANCE OF SEDIMENTS

Preliminary Statement

The beds encountered in the various drillings and excavations in the Dugway area include all those described by Gilbert (1890), and a number of others, not described by Gilbert, whose work was necessarily limited to surface observations. Known extent and significance of these beds will be outlined here, starting at the base of the record.

Red Clays

These clays, known only from the Limbo Well section in the Dugway Area, but also re-

ported from a deep bore near Wendover (70 miles northwest), are apparently a series of playa deposits, and suggest arid conditions, much like those of today. There is no convincing evidence that these are, or are not, Pleistocene beds.

Gray Clays

The gray clays, known only from the Limbo Well (Fig. 2, site 6), apparently represent deposition in a lake, or series of lakes, of unknown extent and some antiquity. Whether the contained sand lenses represent intervals of aridity (playa conditions), or merely periods of turbulent inflow, is not indicated by the bailings.

Major Aquifer

Present wherever the drill encountered any material between the yellow clay and the basal complex, the Major Aquifer apparently underlies the yellow clay in most valley locations in the mapped area. Wherever encountered, it carries fresh water with a high fluorine content, and everywhere southeast of a line between White Rocks and Granite Peak Well (Fig. 2, site 15) it carries much potable water[5]. Known extent of the aquifer, as determined by well logs, has been published elsewhere (Ives, 1949a, Fig. 12).

The porous bed, serving as the aquifer, consists of unsorted coarse sand, gravel, and boulders, of local origin, and seems identical to the sheet wash, pedimental cover, bajada deposits, fans, and gulch dumps now forming in the area. In consequence, the Major Aquifer is classed as a subaerial valley margin deposit, and its areal extent and thickness indicate an arid interval of great duration.

Recharge of the aquifer probably takes place where tongues of valley alluvium extend up through canyons to the surface. In many canyons, small streams are present where the floor is bedrock, but disappear where the canyon floor is alluvium.

[5] Because of changes in level of the aquifer across this line, reduction in the amount of water carried, and increase in its salinity to the northwest, a fault, perhaps an extension of the Fish Springs Fault (Ives, 1946c, 1948e), is suspected here. Displacement of pre-Pleistocene volcanics at White Rocks also suggests such a fault.

A similar aquifer, also contained in a boulder and gravel bed, and carrying fluorine, has been encountered in wells in the Sevier Desert, south of the map area (Fig. 2); and also in a number of wells northwrd, in the direction of Ogden. Although it is quite probable that these aquifers are interconnected, the possibility of hidden discontinuities exists, particularly in the Gilbert River Bed (Fig. 2), where volcanic structures of unknown lateral extent are buried by the yellow clay.

Yellow Clay

The yellow clay, with a few minor exceptions, underlies all of the area formerly occupied by Lake Bonneville, and has a fairly uniform thickness exceeding 200 feet. This material, adequately described by Gilbert (1890), is undoubtedly a quiet-water lake deposit, representing a long time interval. If the laminae present are annual varves, duration of the lake stage in which the yellow clay was deposited was from 15,000 to more than 25,000 years. This lake state, which had a maximum demonstrated height of only 90 feet less than the Bonneville shore line (Gilbert, 1890, p. 190–194), is evidence of the longest continuous submergence of the basin floor yet discovered[6].

Lower Gravel

Definitely identified only at Gilbert's Upper River Bed site, but probably present in numerous valley-wall locations in this area, and in Skull Valley, the lower gravel is a subaerial deposit representing an arid interval of some duration.

White Marl

Present, like the yellow clay, in almost all parts of the Bonneville Basin, and easily identified even from a distance by its white exposures, the white marl is a quiet-water calcareous deposit indicating a submergence of medium duration (6,000 annual (?) laminae).

Numerous exposures of the white marl occur

[6] The name *Escalante*, for Fr. Silvestre Velez de Escalante, first person to report evidence of an ancient large lake (1776) in this area (Ives, 1948a), is suggested for this stage.

on the sides of uplifts, such as Simpson Buttes and Camelback Mountain. Near Granite Peak (Fig. 2), the white marl acquires a banded appearance, due to the inclusion of mica flakes and black tourmaline fragments, eroded from Granite Peak (Pl. 2, fig. 2).

Maximum thickness of the white marl occurs in the Whirlwind Valley area, southwest of the map area (Fig. 2; Pl. 2, Fig. 1; Ives, 1946e), where its fossil content is also at a maximum.

Fine Sand

Immediately above the white marl at both of Gilbert's River Bed sites (Gilbert, 1890, p. 194–196; Fig. 2, sites 38, 39, 40, 42, and 43; Pl. 1, figs. 1 and 2) and in most other parts of the area where the white marl is present, but not the uppermost bed, is the fine sand, a lacustrine deposit, having definite bands in the basal portion. Number of bands per inch is from three to five in most places. Upper part of the fine sand has been reworked subaerially, so that the thickness varies greatly from place to place. Large dunes and ripples are present on the east side of the Gilbert River Bed between Rising Sun (Fig. 2, site 30) and Camelback Mountain. Some post-depositional cut-and-fill bedding was noted in the fine sand near the Old Smelter site (Fig. 2, site 32). Sand of the same composition and thickness as this fine sand is present as dunes atop the Cedar Mountains, a few miles north of the springs (Fig. 2, sites 1, 2, 3), attesting to the great amount of wind erosion and transportation in the area.

Second Gravel

Resting in distinct unconformity upon the fine sand, and its probable correlatives outside of the map area, is the second gravel, a coarse nonfossiliferous deposit, partly subaqueous and partly subaerial, filling channels in the white marl and fine sand, and present only below the Provo shore line. This material is classified as a wave-reworked phase of the surface alluvium produced by arid erosion in this region, and is apparently evidence of a reflooding of the Bonneville Basin after a period of arid subaerial erosion. The second gravel and its equivalents are present only close to highlands.

Upper Sand

The upper sand resting in conformity upon the second gravel, and more than 25 feet thick, is a nonfossiliferous sub-aqueous deposit, of which the upper part has been reworked and partially removed by wind action. This represents a period of active subaqueous deposition, followed (not necessarily immediately or continuously) by subaerial wind erosion, under arid conditions. Like the second gravel, the upper sand is not found above the Provo shore line except as dunes.

Upper Gravel

Upper gravel, a local deposit, rests upon all other beds below the Provo shore line at the Upper River Bed site. It was probably left through removal of the upper sand, in which the gravelly debris was originally included. Some admixture of surface wash is also noted here, and similar deposits, at similar horizons, are common in the area.

Sand-Brine Horizon

Filling the bottoms of wide braided channels eroded into the yellow clay after the general level of the terrain had been lowered more than 100 feet (below the top of the yellow clay), the sand-brine horizon, a nonfossiliferous bed of clean white sand, carrying saturated brine wherever encountered, is evidence of a period of valley filling. The extreme uniformity of the upper surface indicates subaqueous deposition during at least the terminal phase. Absence of definite bedding apparently results from saturation of the horizon during the wetter parts of the year.

White Clay

Resting directly upon the sand-brine horizon in Government Wash and in the southerly parts of Dugway Valley is the white clay, a laminated material resembling reworked white marl plus bentonite. This material, like the sand-brine horizon and the overlying bentonitic clay, is present only below the present 4400-foot contour.

Yeso

The Yeso rests directly upon the Sand-Brine horizon in places where the white clay is absent, and is regarded as a variant of the white clay. It is found only near the Yeso site (Fig. 2, site 9) in this area. Beds intermediate in texture between Yeso and white clay are exposed in bomb craters near Oblivion Junction (Fig. 2, site 20). White clay is found at Dugway and Beulah Station (Fig. 2, sites 12, 13, 14).

Bentonitic Clay

A laminated gray clay closely resembling reworked yellow clay plus bentonite rests upon the White Clay or Yeso, depending upon the area. This material is evidence of a short-lived interval of quiet-water deposition, the bentonitic content strongly hinting at volcanic activity not far away. Upper surface of the bentonitic clay is everywhere wave-planed, and upon it, in a few locations, are bars and benches of gravel, sand, and clay, dating from a recent and minor inundation of the Bonneville Basin (the Dugway Stage).

Surface Wash and Dunes

Extending outward from all highlands in the area are tongues and fans of typical desert alluvium, substantially identical to the buried deposits comprising the Major Aquifer and the lower gravel, except that these surface deposits contain clay derived from erosion of subjacent deposits.

A large number of sand, and sand-clay dunes, composed in large part of local materials, occupy aerodynamically appropriate positions in the Dugway area (Ives, 1946i, Fig. 2). These dunes are still active, but growth and attrition seem to be in approximate balance under present conditions.

Salt Flats Deposits

Surface of the Salt Flats (Fig. 2) is covered with crystalline salt, underlain by Ooze. This material, which is only a few feet above the present level of Great Salt Lake, is probably of almost historically recent origin, and represents deposition during a pluvial stage in which lake waters stood only 25 feet or so above present lake level. Nature of the ooze suggests that the enlarged lake supported some vegetation, which was killed by increasing salinity.

Bare Surfaces

Over more than half of the map area (Fig. 2), the surface is composed of underlying materials, still undergoing erosion and not covered by sheetwash, alluvium, or salt. Much of the stripping of these surfaces is due to wind action, aided at times by the capricious and violent rainstorms common to the Great Basin deserts. Because of rapid removal of mechanically disintegrated material, the surface materials are fresh and differ from those at some depth only because they are bleached and dried by intense desert sunlight.

Summary of Stratigraphic Evidence

General Statement

Stratigraphic evidence from the Dugway area indicates that there were several submergences and emergences at each site. It is also quite clear that the various parts of the area had slightly different depositional histories, particularly during later phases of the record.

Earlier Record

Deeper deposits, and their probable significance, are, from top down:—

Erosional unconformity	emergence
Yellow clay	long submergence
Major Aquifer	long emergence
Lower clays	submergence of undetermined extent and duration.

Intermediate Record

Intermediate deposits, present only at higher levels, about the basin rim, such as Gilbert's Upper River Bed site, are, from top down:—

Eroded surface	emergence
Upper sand Second gravel	submergence
Erosional unconformity	emergence
Fine sand White marl	submergence
Erosional unconformity Lower gravel Erosional unconformity	emergence

The lowest erosional unconformity here is atop the yellow clay of the earlier record.

Upper Record

The upper gravel, dunes, and surface wash, all terrestrial deposits indicating arid subaerial conditions, rest upon the eroded surface of the intermediate record. This same surface, traced to valley floor locations, is substantially identical with the basement beneath later sediments there, and intersects the erosional unconformity separating the yellow clay from the white marl at a point about midway between the Lower River Bed site and Niflheim (Fig. 2, sites 38 and 23, respectively). Atop this erosion surface, overlain by surface wash and dunes in some locations, and present only at low levels, is the following sequence:—

Wave-Planed surface ..... submergence
Erosional unconformity (?) ..... emergence
Bentonitic clay
White Clay—Yeso } ..... submergence
Sand-Brine Horizon
Erosional unconformity atop yellow clay ..... emergence

Emergence

The erosional unconformity (?) atop the bentonitic clay is postulated because fan deposits near Camelback Mountain have been eroded by the shore lines associated with the wave-planed surface atop the clay.

It is interesting to note that the bentonitic clay, white clay-yeso, and Sand-Brine horizon, if stripped of their bentonite content and inverted, are substantially identical to the fine sand, white marl, and yellow clay sequence of the Lower River Bed site (Fig. 2, site 38) and are believed to be reworked materials from that sequence, mixed with bentonite.

Salt Flats Record

The deposits of the Salt Flats area, atop the yellow clay, are still in process of formation, undergo annual inundations, and apparently represent a period of submergence of almost historical recency. Similar deposits form intermittently in adjacent areas today, when the level of Great Salt Lake falls for several years.

Summary of Data

This sedimentary record, with its included hiatuses, indicates that, beginning with the Major Aquifer, the Dugway Area was submerged five times, with an emergence following each inundation. Because the available data do not indicate whether the clay beds below the Major Aquifer were deposited in a lake of 1000 square feet, or of 1000 square miles, their significance remains unknown.

Relation of Sediments to Shorelines

General Statement

In addition to the sediments just described, the area also has a complex series of shore lines, beaches, bars, and embankments in various locations between the 5200-foot contour and the present valley floors. Details of these shore features have been published by Gilbert (1890), and, using more extensive field data, by Ives (1950c), from these data, a number of Pleistocene chronologies have been developed (Gilbert, 1890; Antevs, 1945; Ives, 1950c). These, although not in complete agreement, are in rational accord with the same field data.

Principal shore lines in the Bonneville Basin, with approximate altitudes, are:—

Name	*Altitude*	*Nature*	
Bonneville	5200′	Dual	
Provo	4825′	Triple	
Stansbury	4530′	Dual	
Dugway	4330′	Dual	
Timpie	4245′	Multiple	Groups overlap
Modern	4203′	Multiple	

Observed Relations

Field observations show that some of the shore lines are cut into some of the sedimentary sequences, and hence must be younger than the sediments. Some of the other sediments are deposited on erosion surfaces, also giving an age indication. These relations are:—

The Modern and Timpie shore-line groups are above the Salt Flats, and below all other sediments now exposed.

The Dugway shore lines are above, and in places cut into, the Bentonitic Clay.

The Stansbury shore line is cut into the yel-

low clay and white marl, and is below the upper sand.

The Provo shore line is cut into all members of the Intermediate deposits except the second gravel, upper sand, and upper gravel, all of which are below the shore line, except for doubtful parts of the upper gravel.

Table 1.—Correlation of Sedimentary and Shore Line Records

Stage name	Shore line	Sediments
Dominguez	None known	Lower clays of Salt Flats
Long emergence		Major Aquifer
Escalante	None known	Yellow Clay
Emergence		Lower Gravel
Bonneville	Bonneville	White Marl—Fine Sand
Emergence		Erosion interval
Bonneville-Provo	Provo	Second Gravel—Upper Sand
Emergence		Erosion interval—Upper Gravel (?)
Stansbury	Stansbury	Sand-Brine Horizon—White Clay — Yeso — Bentonitic Clay
Emergence		Erosion interval
Dugway	Dugway	Local beaches, bars and spits
Timpie	Timpie	Salt Flat deposits,
Modern	Modern	beaches, bars and chemical precipitates

Gilbert's Embankment series (1890, p. 108, 127–135), representing the rise of lake waters to a point slightly above the older Bonneville shore line, and the subsequent fall to the Provo level as the outlet at Red Rock Pass was cut down, represents a period of very turbulent lake conditions after the cutting of the Bonneville shore line, and prior to a long-time stabilization at the Provo level. This embankment series rests upon the white marl and fine sand at the southeast end of Bar Hill (Ives, 1950c), and hence is younger than the sedimentary sequence, and also younger than the main Bonneville shore line.

Correlations

The foregoing relations, plus the assumption that no major datum is unrecorded, permit a stage-by-stage correlation of the sedimentary and shore line records which apparently contains no important discrepancies (Table 1).

Correlation of this sequence with the glacial sequences of the Wasatch Mountains is still in the realm of "multiple working hypotheses"; attempts at such correlation have been made by Gilbert (1890, p. 346–348), Blackwelder (1931, p. 914), Antevs (1945) and Ives (1950c). These correlations, similar in many features, all contain undeniable elements of correctness, but disagree in many ways because of varied interpretations of the significance of evidential hiatuses.

Summary of the correlations indicates that the Bonneville and later lake stages are probably of Wisconsin age; that the Escalante lake stage, having no shore lines, is of pre-Wisconsin (perhaps Illinoian) age, and that the Dominguez stage or stages, of unknown magnitude, can be dated only as very much older than the Escalante.

Such a correlation would place the deposition of the beds now constituting the Major Aquifer in the Yarmouth interglacial, and the post-Escalante, pre-Bonneville erosion interval in the Sangamon interglacial. This correlation, although quite plausible, needs a stronger evidential basis before it can be accepted without reservations, and alternative hypotheses, such as that of Antevs (1948), must still be considered.

Notable, in this area, is absence of any really conclusive evidence of either early Pleistocene glaciations, or of extensive early Pleistocene Lakes. This evidential hiatus may indicate that the Bonneville Basin did not become, as a whole, an area of interior drainage until mid-Pleistocene, and raises a question as to the relative height of the Wasatch Mountains during the early Pleistocene.

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Manuscript Received by the Secretary of the Society, June 12, 1950.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 62, PP. 799-852, 23 FIGS. 1 PL. JULY 1951

STREAM GRADIENTS AND MONTEREY SEA VALLEY

By A. O. Woodford

Abstract

The long profile of a mature stream approximates a smooth curve with ever decreasing gradient downstream. This profile curve may be called concave upward, or simply concave. Accurate surveys, mostly of streams in central or northwestern Europe or in the United States, show numerous major or minor deviations from simple smooth profile curves. Most major deviations can be correlated with obvious immaturity. Minor deviations can almost all be correlated with ascertained or probable differences in rock resistance, debris size, or other specific geologic or geomorphic circumstances. In a single region, gradients of mature streams are roughly inversely proportional to a function of discharge. One or more logarithmic curves can be drawn that will more or less closely approximate any given mature profile. General lowering of base level is found to produce a distal profile convexity. Probably such a convexity flattens and loses its initial prominence as it gradually extends upstream, unless localized on resistant rock as a distinct nickpoint.

The Monterey sea valley off California appears on a map to be the approximate seaward continuation of Salinas land valley, but its head is cut into alluvium deposited by Salinas River and adjacent streams, its irregular upper profile is nearer to an exceptionally steep straight line than to a logarithmic curve, and the compound Salinas-Monterey long profile shows an extremely pronounced break or nick on weak sediments at the shore line. Therefore it is considered improbable that the Monterey submarine canyon is the product of subaerial rejuvenation of the Salinas or any other land river. Most other sea valleys with steep gradients appear to be essentially similar to the Monterey; the Congo canyon is ambiguous and may be exceptional.

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Introduction

General Statement

Profiles along Monterey and other sea valleys have been published by Shepard and Beard (1938), and compared to those of land valleys. Shepard (in Shepard and Emery, 1941) apparently favored a subaerial origin for sea valleys or submarine canyons. The present writer considers the form and steepness of the profiles important. However, geomorphologists hold such varied views concerning the significance of stream gradients[1] that it seems desirable to discuss these gradients rather thoroughly before comparing land and submarine valleys.

Many stream profiles are fairly smooth curves concave upward[2], similar to each other whatever may have been the initial shape of the land surface. As radial ravines are sunk into the even slope of a volcanic cone, the ravine gradients become steeper near the summit, and less steep downstream. Similar developments occur on the relatively flat surface of a tilted fault block such as the Sierra Nevada, on an anticlinal or domed uplift, or on blocks of less regular shape. It is especially easy to reconstruct the structural surface in the case of a simple anticline. The Kettleman Hills, in California's Great Valley just northeast of the Coast Ranges, are the eroded remnants of such a fold of Tertiary and Pleistocene sediments. The present relief of 500 or 600 feet is only about an eighth of the height of the eroded portion of the dome (Fig. 1). Past erosion has probably involved through-going streams, as well as the local ones now active. A smooth old surface is partially preserved in the highest parts of the summit level shown by a dashed line on Figure 1. The old surface is gently convex. Considering only later erosion, a real or potential convexity has been transformed into the concave gradient curves of two sets of opposed ravines. What determines these gradients? Are they fixed at every point by the conditions of their formation, and, if so, are those conditions determinable? These questions will be considered in the general part of this paper. Some hydraulic generalizations developed by engineers will be mentioned, but with-

[1] For a point of view minimizing the significance of the stream profile see Kesseli (1941).

[2] Concave if the earth's convex sea-level surface is considered plane.

FIGURE 1.—SECTION THROUGH KETTLEMAN HILLS, CALIFORNIA
Data from U. S. Geological Survey Professional Paper 195 (1940)

out attempting to cover the field even in an elementary fashion. Then stream profiles will be considered, emphasizing first the several factors affecting stream gradients, and second, the process of stream incision. Finally, the principles established for land valleys will be applied to the Monterey and a few other sea valleys.

The chief object of the paper is to test once more a basic geomorphic generalization by study of the field facts. The application of the conclusions to the sea valleys is a secondary objective.

Acknowledgments

This study was commenced in 1931, in cooperation with Professor Edward Taylor of Pomona College. The present paper owes much to his work and advice, but was written during 1946 and 1947, while Professor Taylor, now emeritus, was absent from Claremont. Many Pomona College students collaborated in field and office work. These students included Edwin Ogier '32, Thomas Berry '32, Rodman Cross '33, Mary Galbraith, Thomas Peterson '38, Melvin Swinney '40, Wallace Wilson '40, Edmund Brand '42, Jack Schoellhamer '42, Martha Ryder Smith '42, Frances Kendall Moran '48, John G Vedder '48, Thane McCulloh '49, Wayne Burnham '51, and Willis Burnham '51. Mechanical analyses of samples from the Kettleman Hills were made at Stanford University with the assistance of Alexander Tihonravov.

Well logs and other information were furnished by Dr. P. P. Goudkoff, T. Russel Simpson of California Division of Water Resources, the late Dr. R. W. Clark of Western Gulf Oil Company, J. C. Kimble and Peter Gardett of General Petroleum Corporation, Professor C. Noble Beard of Fresno State College, A. T. Vierra of Moss Landing, California, and C. W. Johnson of Richfield Oil Corporation. Engineers of the Water Resources Division, U. S. Geological Survey, supplied abundant data, from which were selected most of those used in Table 1 and Figure 4. The U. S. Coast and Geodetic Survey kindly furnished photostat copies of unpublished charts of the sea floor off the central California coast. Dr. R. Dana Russell, formerly of Louisiana State University, and Dr. J. R. Schultz of the Waterways Experiment Station, Vicksburg, Mississippi, provided data concerning the Mississippi River.

Professor Eliot Blackwelder of Stanford University gave some suggestions concerning geomorphic nomenclature, but does not necessarily concur in all the usages of this paper. Dr. John Crowell, University of California at Los Angeles, Professors Edward Taylor and John Shelton, Pomona College, Professor Hoover Mackin of the University of Washington, Professor C. C. Albritton of Southern Methodist University, Professor W. D. Thornbury of Indiana University, and Douglas M. Kinney of the U. S. Geological Survey kindly criticized the manuscript. As Mackin's (1948) paper on the graded river covered part of the same ground, the original manuscript was put aside, and revised in 1950, with the addition of the final sections on selected Atlantic valleys and on the geomorphic effects of Pleistocene change of base level.

Research grants were provided by the American Association for the Advancement of Science, Claremont Graduate School, and the Geological Society of America.

Definitions

The longitudinal profile along the course of a stream or drainage line, *long profile* for short, is obtained by plotting horizontal distances from mouth (or source) against elevation of the water surface. Small streams are so shallow that their profiles may fairly be compared to those of dry ravines. Large, deep rivers, on the other hand, have markedly different bed and surface profiles, and near their mouths flood profiles may be notably steeper than the low water gradients. Stream gradients are usually so low that vertical exaggeration is necessary to emphasize changes. The exaggerations used in the accompanying figures range from 2 to 1000.

Gradient is used for slope expressed in per cent, feet per mile, or other convenient units. *Grade* is used as a geomorphic term, in connection with the mature profile.

A *gradient curve* may be constructed by plotting the slopes of successive short stretches against the distances from mouth or source (O. T. Jones, 1924). Mathematically such a curve is the first derived curve of the long profile.

A *nickpoint*[3] is a relatively sharp break in the long profile, with a flatter gradient above, a steeper one below.

Distinctions may be made between the *upper course*, *middle course*, and *lower course* of a stream (Fig. 2), at least in the case of a mountain torrent that has much steeper gradients than the river or basin into which it empties (Albert Heim, 1878, p. 293–295; Rehbock, 1930). Such a torrent builds a debris cone at its mouth. As first formed, the cone has a steep surface. Then the stream cuts down in its upper course, above the cone head, until it entrenches itself into the cone or fan head at a lower gradient, forming a fan-head trench (Eckis, 1928), and commonly finally debouching upon the lower part of the cone, raising and extending it by deposition (dashed line of long profile in Fig. 2), before discharging into the mountain river.

The *lower course* (C in Fig. 2) is the stretch that is always on the cone, the *middle course* (B in Fig. 2) is the stretch that is alternately the site of deposition and of erosion (Albert Heim, 1878, p. 293–295). The existence of the middle course has been doubted by Kesseli (1941), but as here defined it is present in hundreds of cases (see Eckis, 1928, 1934).

If a stream meanders in a flood plain or has a course which is at all sinuous or crooked, in a well marked straighter valley, then we may be interested in the gradient of the valley as well as that of the stream. It becomes desirable to have a name for the line down the center of the well marked valley. The term commonly used, *talweg* (thalweg, see A. Penck, 1894, vol. 2, p. 73; Cotton, 1922, p. 6) is here replaced by *valley axis*, because talweg has at least two other meanings to some engineers or geologists (Fig. 3). The valley axis (talweg 1) is the surface profile along the center line of the valley. Talweg 2 follows the same course, but is taken on the bedrock surface. Talweg 3, used by most American engineers, including those of the Mississippi River Commission, and perhaps also by the Englishman J. F. N. Green (1934), follows the bed of the river along the line of the main (and deepest) channel. De Martonne (1927, p. 149) probably followed usage two, possibly three. A meandering stream may be two or three times as long as the valley axis. Even the principal channel of the braided Durance, between Mirabeau and the Rhone, is 6.3 per cent longer than the axis of the "*champ de gravier*" (de la Brosse, 1916, vol. 7, p. 46).

[3] Commonly spelled knickpoint (German *Knickpunkt*.

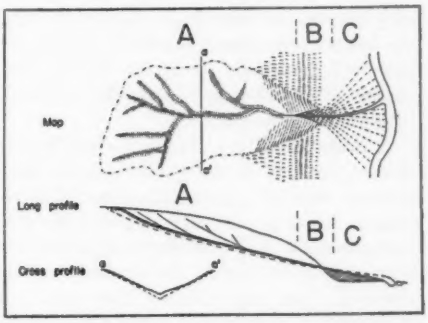


FIGURE 2.—AA UPPER COURSE, BB MIDDLE COURSE, CC LOWER COURSE OF TORRENT
After Rehbock (1930).

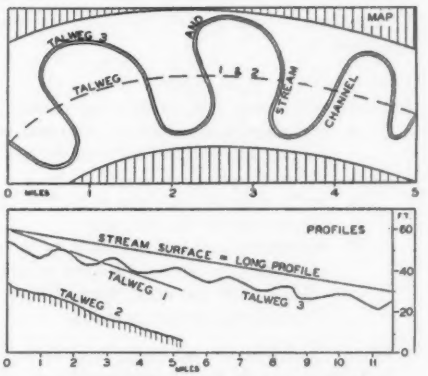


FIGURE 3.—TALWEG AND VALLEY AXIS (TALWEG 1)
Scale for profiles 0.4 that of map. See text for explanation.

Ridge profiles may be plotted from interfluve lines roughly parallel to the courses of the streams in question. They are much less definite than stream profiles. Their preparation involves more choice and judgment.

HYDRAULIC FACTORS

In Streams

Slope, form of cross-section, bed roughness, and velocity.—Engineers have long recognized equi-

librium conditions in many natural and regulated streams. In 1697, Guglielmini (quoted by Baulig, 1926) stated five fundamental qualitative propositions: (1) Streams erode or build up their beds until equilibrium is attained between force and resistance; (2) slope will therefore vary inversely as velocity; (3) slope will be less, the less the resistance of the bed materials; (4) slope will vary inversely as the ordinary discharge; (5) a mobile bed is modified to give a long profile concave upward.

A. Brahms (1753 ?, quoted by Ganguillet and Kutter, 1889, p. 3) stated that streams have constant velocity instead of the expected acceleration due to gravity. He suggested that the friction against the wetted perimeter is the force that opposes and equals the acceleration, and assumed that this friction [per unit of discharge?] is proportional to the area of cross section divided by the wetted perimeter.

Physical theory and engineering experience led to the formulation by de Chézy (1775, *see* Forchheimer, 1930, p. 139, footnote) of the equation:

$$V_m = C\,(RS)^{\frac{1}{2}}$$

where V_m = the mean value of the linear velocity,
R = the hydraulic radius, equal to area of cross section divided by wetted perimeter,
S = the slope of the water surface (with uniform cross section), and
C = Chézy's coefficient, thought to be a constant by Chézy and later a constant only for given conditions, especially of channel roughness.

Many modifications of Chézy's coefficient have been proposed. Also, since Humphrey and Abbot's (1861) report on the Mississippi, R has usually been weighted in one way or another. Among the simpler modifications still in use are those of Manning (Forchheimer, 1930, p. 146) and Forchheimer (1930, p. 147). Manning used a roughness coefficient n, and the equation became $V_m = \frac{1}{n} R^{2/3} S^{1/2}$, using meters, or $V_m = \frac{1.49}{n} R^{2/3} S^{1/2}$, using feet. Forchheimer substituted λ for $\frac{1}{n}$ and changed the R exponent slightly. His equation is $V_m = \lambda R^{0.7} S^{0.5}$. The coefficient λ varies inversely as bed roughness.

Forchheimer (1930, p. 147) reported a λ range of 24 to 30 for natural rivers, and Daugherty (1937, p. 272) n 0.025 to 0.060 for weed-free streams. The ranges for streams large and small may be even larger than Daugherty's, as suggested by Table 1. The French data were selected by resident engineers to obtain Chézy-type coefficients for local use. The American observations do not yield values for the coefficients that could be used as engineering standards, chiefly because some slopes are doubtful. Cross sections at or near most of the Table 1 gaging stations are shown in Figure 4. Table 1, No. 1, and Figure 4A represent a small mountain river, the Isère, constrained by steep banks and gaged between the piers of a bridge at a relatively low stage. The mean of 21 λ determinations for this station, based on 1905–1908 data, was 32; the range 27–44, the 44 being a flood value and the only one over 37. At a station with a steeper (.004) gradient, 27 km. downstream, gaged 11 times during 1905 and 1906 at low or medium stages (de la Brosse, 1908, p. 28), λ was 25–30. A large, deep, relatively clear river, such as the Columbia at flood (Fig. 4B and Table 1, No. 2) has a relatively large R and high velocity, whereas the Platte, broad and shallow on the plains, shown in Figure 4C and Table 1, No. 5, at a relatively high stage, has a low R and low velocity for its slope. These two very different rivers have practically identical λ's of 30 and 29, but the corresponding C's are 51 and 32, respectively.

A stream increases in velocity with increasing discharge. If the cross sections and slopes are known, the new velocity may usually be estimated fairly closely with the aid of a Chézy-type formula. The coefficients at some stations, however, may change considerably at discharge. Though λ for one station on the upper Isère was about the same at all stages, λ for the other dropped from 44 at flood to 33 a few weeks later. The Colorado near Lee's Ferry (Table 1, Nos. 6 and 7, and Fig. 4D) apparently is distinguished by very high λ at low water, with decrease at flood. The effective slope for No. 6 is estimated, that for No. 7 is not known but may actually have been steeper than for No. 6. The high λ at this station may be related to the high sediment content of the water.

A second measure of the form of cross section, also shown in Table 1, is the *form ratio*, mean

TABLE 1.—HYDRAULIC DATA FOR SELECTED RIVER STATIONS

	Date	Width	Area of cross-section	Wetted perimeter	Hyd. radius (R)	Mean Velocity	Discharge	Slope (S)	C	λ	n	Form ratio
1. Isère R., at Montrigon, France, 38 kms from river's source	Jan. 26, 1906	78.8 ft 24 m	155.2 ft² 14.42 m²	85 ft 26 m	1.9 ft .56 m	1.83 ft/s 0.557 m/s	28.4 ft³/s 8.05 m³/s	42 ft/mi 0.8 m/km	47 26	30	.034	1:39
2. Columbia R., at International Boundary	June 12, 1948	900 ft 274 m	42,300 ft² 3,930 m²	918* ft 280* m	46.1 ft 14.1 m	12.62 ft/s 3.85 m/s	534,000 ft³/s 14,950 m³/s	2.2 ft/mi 0.4 m/km	93 51	30	.030	1:19*
3. Columbia R., near The Dalles, Oregon	May 31, 1948	1960 ft 597 m	92,600* ft² 8,600* m²	2,000* ft 610* m	46.3* ft 14.1* m	10.99 ft/s 3.35 m/s	1,018,000 ft³/s 28,500 m³/s	1.5 ft/mi 0.3 m/km	93 51	30	.030	1:42
4. Columbia R., near The Dalles, Oregon	July 2, 1948	1540 ft 469 m	72,240* ft² 6,714* m²	1,575* ft 480* m	45.9* ft 13.98* m	7.24 ft/s 2.22 m/s	523,500 ft³/s 14,825 m³/s	? ?				1:33
5. Platte R., near Duncan, Neb.	June 25, 1947	880 ft 268 m	4,840* ft² 450* m²	890* ft 271* m	5.4* ft 1.65* m	4.19 ft/s 1.28 m/s	20,300 ft³/s 568 m³/s	5.6 ft/mi 1 m/km	57 32	29	.035	1:160*
6. Colorado R., near Lee's Ferry	Apr. 11, 1928	374 ft 114 m	2,480 ft² 231 m²	380* ft 116* m	6.5* ft 2.0* m	6.29 ft/s 1.9 m/s	15,600 ft³/s 437 m³/s	1.7 ft/mi 0.3 m/km	137 78	67	.014	1:56
7. Colorado R., near Lee's Ferry	June 4, 1928	437 ft 133 m	11,810 ft² 1,098 m²	452* ft 137* m	26.2* ft 8.0* m	9.31 ft/s 2.8 m/s	110,000 ft³/s 3,080 m³/s	1.7?ft/mi 0.3?m/km	101? 57?	37?	.025?	1:16

No. 1 from de la Brosse (1908, pp. 31–36), Nos. 2–7 from U. S. Geol. Survey data, mostly unpublished. Slope for No. 5 from U. S. Geol. Survey Water Supply Paper 44.

* Estimated from U. S. Geol. Survey data. Ft, feet; m, meters; mi, mile; km, kilometer; s, second; C, Chézy coefficient; λ, Forchheimer's coefficient; n, Manning's coefficient.

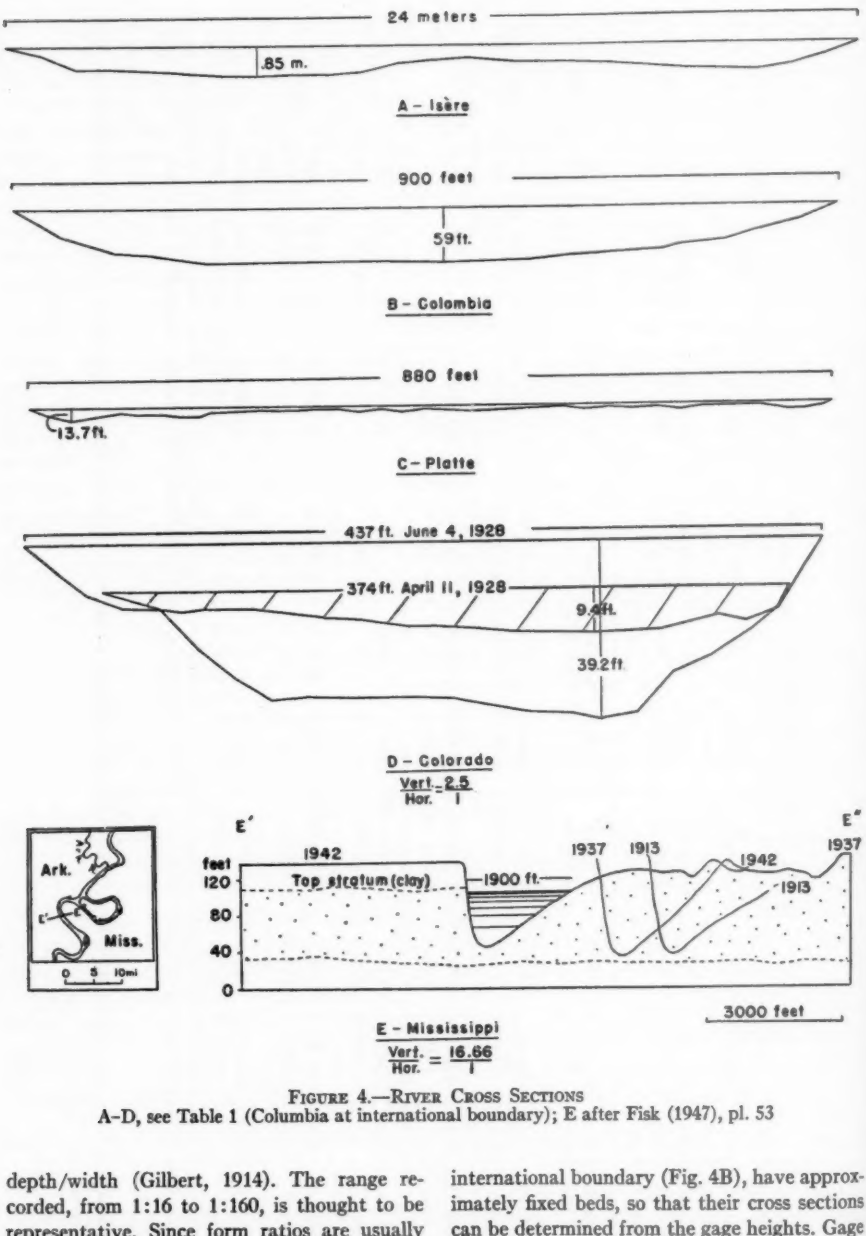


FIGURE 4.—RIVER CROSS SECTIONS
A–D, see Table 1 (Columbia at international boundary); E after Fisk (1947), pl. 53

depth/width (Gilbert, 1914). The range recorded, from 1:16 to 1:160, is thought to be representative. Since form ratios are usually such small fractions, hydraulic radii are usually practically identical with mean depths.

Some rivers, such as the Columbia at the international boundary (Fig. 4B), have approximately fixed beds, so that their cross sections can be determined from the gage heights. Gage readings for the Colorado near Lee's Ferry (Fig. 4D), on the other hand, would be less useful because of the large annual changes due to

scour and fill. A cross section at a Mississippi bend (Fig. 4E) may be easier to estimate from a gage height, despite lateral migration.

Table 1 emphasizes, and perhaps slightly exaggerates, the ranges of the coefficients. Compilations from engineering data (Daugherty, 1937, p. 272) give confidence that the variations are not random, and indicate that the Chézy-type equation is an effective tool in canal and river engineering. Perhaps even the Forchheimer form weights R insufficiently for flood discharge. The choice of coefficient should be based on a careful study of the conditions, probably including debris load as well as channel roughness. The equation is an impressive generalization about velocity. It should not be applied blindly by geomorphologists, but its implications should not be ignored by them, either.

Types of Flow.—Obviously Chézy assumed a single type of flow, but we cannot do so. Nonturbulent (laminar or streamline) flow is almost never observed in rivers, but it is quite probable in a sea valley. Two states of turbulent flow, also, should be distinguished: streaming and shooting. The critical current velocity, at which streaming flow changes to shooting flow, is given by the equation (Rehbock, 1930)

$$V_c = (gd)^{\frac{1}{2}}$$

where g = the acceleration of gravity,
d = the depth of the current, and
V_c = the wave velocity for the given depth.

Shooting flow is relatively rare, especially in large streams. In shallow streams the limiting velocity is much less and shooting flow may occur, especially for short distances, alternating with streaming flow. In streaming flow, waves can be propagated upstream. In shooting flow, waves can only be propagated downstream, resulting there in a surface covered by rhomboid ripples (Fig. 5). Where streaming flow changes to shooting flow, the simplification of the turbulence results in increase of velocity and a consequent lowering of the water surface. Where shooting flow becomes streaming flow, these changes are reversed. In particular, the surface of the water rises downstream, making what is known as the hydraulic jump, with its accompanying horizontal eddy or roller.

The lower limit of turbulent flow of clear water can be predicted roughly from the Reynolds number (R). Reynolds' equation may be written

$$R = \frac{v \cdot m}{\nu} \qquad \text{(Hjulström, 1935, p. 234)}$$

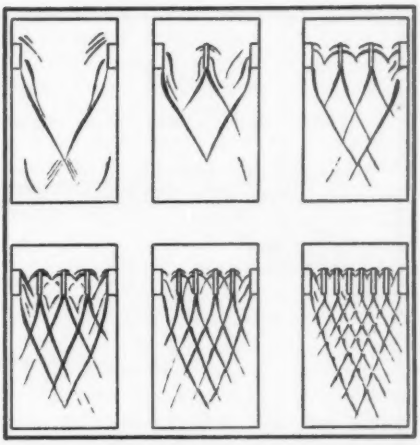


FIGURE 5.—DIAGRAM SHOWING RHOMBOID RIPPLES ON WATER SURFACE BELOW PIERS, IN SHOOTING FLOW
After Rehbock (1930).

where v = the average velocity for a given cross-section
m = the hydraulic radius (called R on a previous page)
ν = the kinematic viscosity of the fluid (viscosity divided by density)

Measurements have given critical values of R, marking the lower limit of turbulent flow, between 180 and 2000 for pipes, and between 144 and 900 in open conduits (Schoklitsch, 1937, p. 69). According to Hjulström (1935, p. 237–243) the critical values in streams are usually between 300 and 600, making the critical velocities only fractions of a millimeter per second. Since viscosity varies greatly with temperature, the critical velocity for water at 25° C. is only half that at 0°.

Horton, Leach, and Van Vliet (1934) proposed, as a more exact measure of the lower limit of turbulent flow in open channels, the Horton criterion, which is, in c g s units (Hjulström, 1935, p. 238):

$$V_H = 0.021 \cdot \frac{\nu}{n^2 \cdot d^{1/3}}$$

where ν = the kinematic viscosity
n = Manning's coefficient of roughness of the channel
d = the depth of water

at or near the bottom of a current. They are at least in part a load on the energy of the current, rather than a part of the gravity-propelled liquid. The transportation of debris by running water has been the subject of many studies (Hjulström, 1935, p. 265–346; Gilbert, 1914;

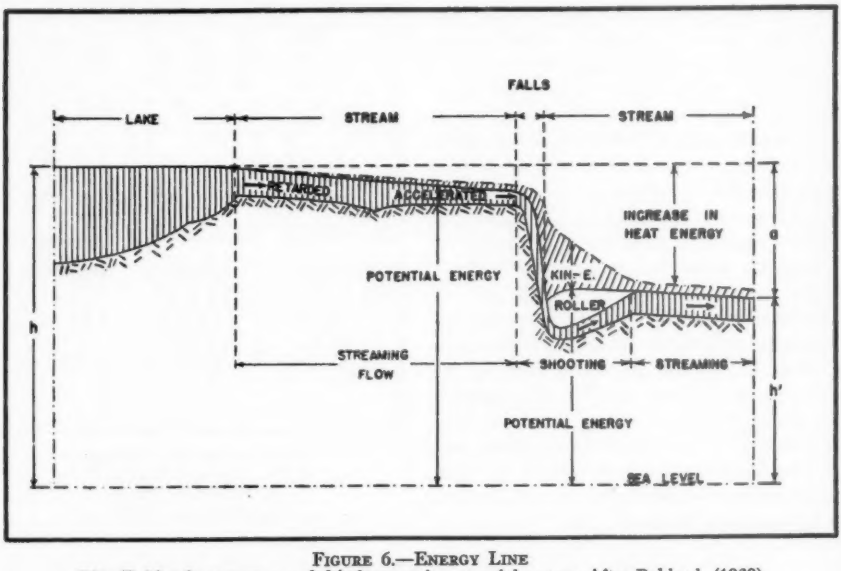


FIGURE 6.—ENERGY LINE
Kin.-E, kinetic energy. a = h-h', decrease in potential energy. After Rehbock (1930)

Hjulström (1935, p. 243) demonstrated experimentally the correctness of the Horton criterion for movement over a sandy surface.

Energy of stream flow.—Since 1875, many discussions of stream flow, especially those involving debris-carrying capacity, have emphasized energy relationships. Rehbock (1930) used an energy line to represent graphically the sum of the kinetic and potential energy (Fig. 6). This is an especially useful device in connection with the change of velocity and turbulence at the point of change from streaming to shooting flow and vice versa.

Debris load.—For natural streams, the treatment of turbulence is complicated by the presence of clay, silt, sand, and gravel. Clay, which remains indefinitely in suspension, may be treated as part of the fluid. Sand, gravel, and, to a lesser degree, silt are usually concentrated

Vanoni, 1946). H. A. Einstein (Am. Geophys. Union, California Institute meeting 1947) has pointed out the difference in behavior of suspended load and bed load, and has suggested that their transport is determined by different laws. Rubey (1933b; 1938) has emphasized the double nature of the problem—competence and capacity—and the geological significance and methods of estimation of bed velocities.

The competence of a current is measured by the largest particles that it can keep in suspension or move along its bed. Nevin (1946) presented data and diagrams illustrating very clearly Rubey's (1933a) distinction between the settling of silt and clay according to Stokes Law, the settling of gravel according to the Impact Law, and the settling of sand between ⅛ and 1 mm diameter at intermediate rates. Under Stokes Law, diameters vary as the square roots

of velocities, under the Impact Law as the squares of velocities. Nevin devised a traction tube method for the study of bed load movements, by which it was found that mean velocities for traction (much greater than those for suspension) can be related to suspension under the Impact Law by Rubey's (1938) equation for estimating bed velocities.

Vanoni (1946) found that suspended load reduced resistance to flow and increased velocity. The presence of 1.2 grams of fine sand per liter reduced Manning's n as much as 10 per cent (1946, p. 102). Apparently the increase of velocity was due to a lessening of the turbulence. Possibly the abnormally high velocity of the turbid Colorado (Table 1, No. 6) had a similar cause. In the discussion of Vanoni's paper (1946, p. 114–116), A. A. Kalinske, on the basis of his earlier experimental findings at Iowa with sediment much finer than Vanoni's, questioned the effect of suspended material on turbulence and on the hydraulic characteristics of the flow.

Vanoni (1946, p. 130) considered vertical lift by eddies an important factor in bed load movements. White (1940; quoted by Kalinske, 1947, p. 616) concluded that vertical lift is negligible for bed load movement. Kalinske (1942) defined saltation as bounce, and showed that bounce is unimportant in sand transport. Having eliminated saltation from separate consideration, he later (1947) developed a shear formula for evaluating the rate of movement of bed load. Kalinske found that his equations gave values similar to those determined experimentally by several workers or groups of workers.

Obviously complete agreement on the laws of sediment transport has not yet been reached, even for the ordinary thin suspensions, or bed movement by currents of clear water. The extraordinary behavior of the thick suspensions called mud flows has long been known in arid regions, and the possibility of similar subaqueous turbid currents or flows has been demonstrated by several authors (e.g. Albert Heim, *et al*, 1888; Kuenen and Migliorini, 1950).

Meaning of load and overload.—Gilbert (1877, p. 107) defined maximum load (capacity) as follows:

> "As the energy expended in transportation increases, the velocity diminishes. If the detritus be composed of uniform particles, then we may also say that as the load increases the velocity diminishes. But the diminishing velocity will finally reach a point at which it can barely transport particles of the given size, and when this point is attained, the stream has its maximum load of detritus of the given size."

Gilbert thus derived a definition of load capacity through assumptions partially contradicted by Vanoni's (1946) data.

Many streams in their upper or middle courses are not loaded to capacity by any definition. First, consider competence and its relation to load. Competence is a direct or indirect function of mean velocity, and slope is one of the factors that determine velocity. Tributaries with very steep gradients may have such high flood velocities that they can furnish a river with debris beyond its competence even at flood stage. The Colorado River shows many illustrations of this effect. Most of its famous rapids are caused by low dams formed by coarse boulder fans dumped into the river's gorge by steep tributaries (Fig. 7). As described by Maxson and Campbell (1935), the river, even with the maximum velocities resulting from flood flow down the steep slope at a rapids, cannot move the great boulders but merely cuts into them, gradually reducing them to sizes that can be rolled down stream. In the rapids the river is not loaded; neither does it pick up the debris over which it flows. Competence is obviously a limiting factor in sediment transport.

Inside the limits set by competence, capacity is hard to measure, even in small experimental channels. If a bed is mobile, a change from erosion to deposition, or vice versa, may occur at one or more points, with resulting changes of bed gradient and velocity. If the bed is fixed, the experimenter cannot be sure that he is measuring the exact capacity for the sizes and type of debris furnished. Finally, the capacity for a single size of debris is to some extent dependent on the amounts of other sizes present. Fine silt and clay may act as part of the liquid, changing its density and viscosity, perhaps with resulting actual increase in the capacity (and competence) of the current to transport larger particles. The problem is so elusive that Quirke has concluded: "The whole attempt to relate capacity (as defined by Gilbert) to the measured velocity of a stream or to the discharge of a

trough is fraught with frustrations" (1945, p. 130).[4]

Field studies from the time of Surell (1841) and Gilbert (1877, p. 113) on have indicated that most streams establish stable gradients when at or near flood flow, when their velocity is greatest, and make only minor readjustments during periods of medium or low water. The actual load of any river at a given water stage is limited by competence and by the sizes and shapes of the fragmental material available for transportation. Perhaps no stream is ever so loaded with solid debris that no particles of any size can be added without causing other elements of the load to be left behind. The behavior of actual streams, whether regulated or unregulated, does suggest that some rivers or parts of rivers, at their most effective stages, are loaded to capacity with at least some of the sizes of material available for transportation, and that other streams or stream sections are not loaded to capacity at their most effective stages (Mackin, 1948). For a loaded stream, any disturbance of hydraulic conditions—for example, removal of load by a dam—results in a compensatory change, such as accelerated erosion below the dam. Just such erosion has occurred in the bed of Colorado River below Hoover Dam, even under regulated flow (Stevens, 1938). Similar erosion was a factor in the breaching of a dam across Yuba River, California (Gilbert, 1917, p. 52–60).

Evidence as to capacity, only slightly complicated by competence, is sometimes furnished by the behavior of streams in a volcanic region after a great ash fall. Arroyo de Corucjuata, 3 kms. west of Parícutin volcano, Mexico, winds through hills for 2.5 kms. at an average gradient of 10 per cent for the last 2 kms., and then debouches into a broad valley, the gradient dropping to 6 per cent (Segerstrom, 1950, p. 108). One day in the summer of 1945, after very heavy rainfall, Corucjuata stream acquired a large load of volcanic ash and boulders, much of which it deposited as a slightly convex alluvial fan several hundred meters wide and extending 600 meters outward into the broad valley. As the waters subsided they cut a trench through the fan, which was deepened by subsequent, somewhat smaller floods of the 1945 season to a fanhead depth of 6 meters, just sufficient to cut entirely through the fan deposit. Almost all the ash of the fan will pass a 30-mesh to the inch screen and be caught on a 200-mesh screen. Boulders sparsely distributed through the ash or lying on its surface were mostly large, 1 or 2 meters across. These boulders were carried downstream by the floods which excavated the trench. Corucjuata stream may properly be said to have been loaded, or even overloaded, with sand at the crest of the first and largest flood flow, but not loaded at later stages. The movement of the boulders was probably made possible by sediment loads as high as 80 per cent, that made the density of the supporting medium as high as 2.08 (Segerstrom, 1950, p. 107).

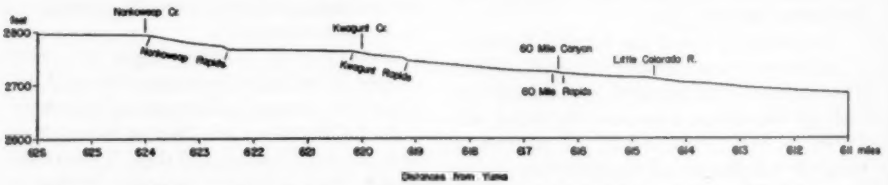


FIGURE 7.—STEEPENING OF COLORADO RIVER GRADIENT BY BOULDER DAMS NEAR MOUTH OF LITTLE COLORADO

Vertical exaggeration 52.8×

[4] Incidentally Quirke stated (1945, p. 129) that a natural stream applies a relatively small portion of its available energy to load transporation. Using Humphreys and Abbot's (1861) data and equation, he pointed out that the Mississippi River at Columbus, Kentucky, has an actual velocity "90% of the theoretical velocity" established by Humphreys and Abbot on the assumption of no bends or other obstructions to free flow. As the Humphreys and Abbot equation was in part empirical, based on Mississippi and other observations, Quirke's use of the term "theoretical velocity" might be misleading.

In general at Parícutin in 1945, a small waxing flood was much more heavily loaded with ash than even a large waning flood. Apparently cave-ins during waxing kept the stream charged. During waning, the waters in their upper courses were flowing on scoured beds; they were thus without much load when they encountered previously deposited ash downstream (Segerstrom, 1950, and oral communications).

Overload, as used by various authors, appears to mean the condition prevailing just before, or at the moment of, appreciable deposition. Deposition then becomes proof of overloading, or another way of stating that overloading existed.

Kesseli (1941, p. 567, 580), commenting on Surell's description of Alpine torrents, seems to have overlooked the importance of competence in the trenching of a fan by the stream that built it. Surell (1841, p. 137) had described a trench in a fan beside the Durance River as having been cut at an epoch immemorial, though not before the first appearance of men in the region, as indicated by artifacts found deep in the old cone. Kesseli concludes: "The torrent changes to a brook and, in spite of decreased volume, cuts a trench into the deposits which the more powerful torrent formerly could not dissect." As I read Surell, his description does not necessarily imply that the stream which traverses the trench is always small, much less that the stream which initiated the trench was small. Fanhead trenches are common in many parts of the world. Surely where the fanheads are made up of great boulders trenches are not cut at times of low water. Probably they are cut at flood stage, initiating a definite new period in the history of the stream's middle and perhaps lower course (*see* Eckis, 1928).

Summarizing, load is obviously or by definition limited by competence and capacity, which in turn are functions of a whole series of hydraulic factors. The suspended load may itself change velocity and turbulence, so that suspension capacity (or capacity in general) cannot be derived from the flow characteristics of clear water. It is almost impossible to measure a capacity load directly. Moreover, the term loaded stream is meaningless unless the grade size or sizes are indicated. The best geological test of capacity is the pragmatic one. If a stream has built a deposit, it was loaded and overloaded at some time along that particular stretch with debris of some sizes and shapes.

Local Currents in Extensive Water Bodies

Currents caused by small differences of density in the clear waters of the deep oceans will not be considered here. Currents in smaller water bodies or along the margins of the oceans may be propelled by greater density differences due to local turbidity. Bell (1942) and Kuenen and Migliorini (1950) have described relatively heavy turbid water masses in large troughs and in reservoirs, that flowed as bottom currents beneath clear water, with the development of surface irregularities with shapes somewhat like cauliflower clouds.

Silty Colorado River water has moved as a turbid density current along the bottom of Lake Mead to its outlet at a velocity of about 0.8 feet per second (Bell, 1942, p. 522). This current probably moved turbulently despite its low velocity and slight mixing with the overlying clear water.

Flows generated by landslips may be more significant than those arising directly from muddy streams. Many landslips into water bodies are known, and a few, especially in Switzerland, have been carefully studied. The celebrated flow of 1887 into the Lake of Zug, Switzerland (Albert Heim *et al.*, 1888; Arnold Heim, 1908), may have had an initial velocity of several meters per second, with resulting turbulent flow, and yet it moved as a bottom current that first eroded a trench in the lake floor and then spread out as a delta-like tongue 200–250 meters broad and up to 4 meters thick, with its toe 1020 meters from the point of origin at the shore line (Fig. 8).

The details of the Zug 1887 flow were somewhat complicated. Part of the city of Zug is built on an old delta of unconsolidated sand. In 1884 the city quay was extended part way across a shallow inlet alongside this delta, by driving a line of piles in water 1 to 7 meters deep and filling in with masonry, loose stone and refuse, along and behind the piles. Cracks appeared in the new land, experts were called in, and a fairly complete sublacustrine survey was made, showing among other things, a rubble slope of 70 per cent gradient to a depth of 7

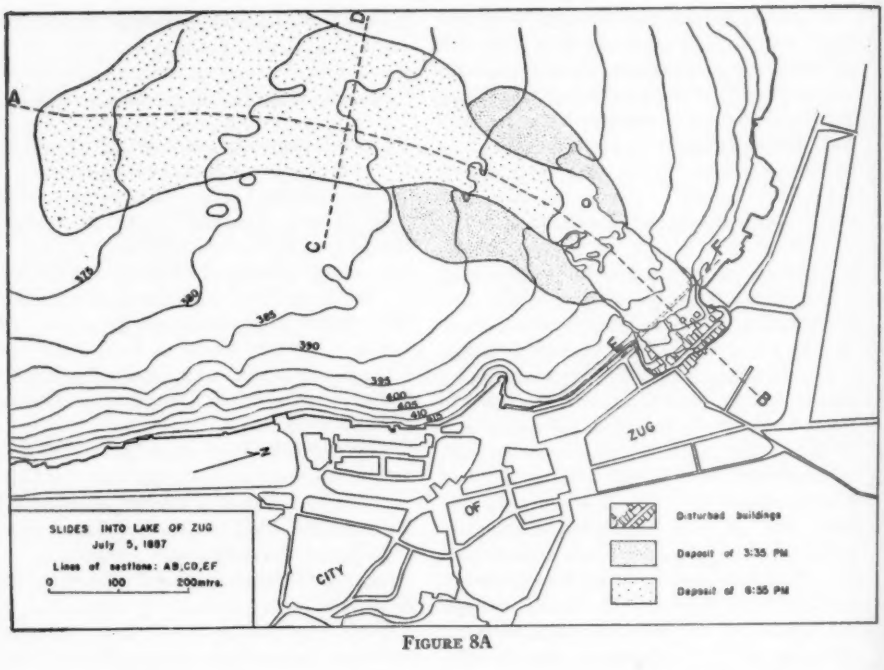


FIGURE 8A

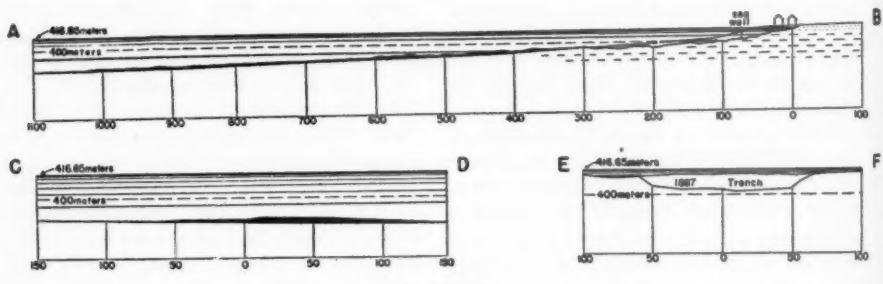


FIGURE 8B

FIGURE 8.—SLIDES INTO LAKE OF ZUG, SWITZERLAND
Elevations above sea level, in meters

meters just outside the piling. Work was then resumed, but on July 5, 1887, the still unfinished project was disastrously terminated by two underwater slides. First, at 3:35 p.m. a short section of sea wall and two houses sank suddenly beneath the lake, with the loss of seven lives. A half hour later some of the piles rose to the surface 100 meters off shore. Concentric parallel cracks in the ground then appeared and several wooden huts crumpled. About 6:50 p.m. great commotion out in the lake was noticed, and at 6:55 strip after strip of land subsided, beginning at the lake shore and extending inland until, in just a few seconds, a place 150 meters along the quay and reaching 80 meters inland had sunk 7 or 8 meters, the houses being wrecked and partially submerged but not torn to pieces or moved much laterally. Only about half the sunken area was newly made land.

A post-disaster survey that included 3200

soundings showed a trench extending 300 meters off shore and two hummocky deposits, the earlier trenched by the later (Fig. 8). The maximum fall was from 2 meters above the lake surface to 44 meters below it—the average slope 4.4 per cent. The slope of the first 100 meters of the trench was much steeper, about 12 per cent. The volume of material displaced by the slide and lake-floor trenching was estimated to be about 150,000 m^3, that of the deposits 250,000 m^3. The discrepancy is due in part to the inadequacy of the 1884 survey and in part to the water included in the newly deposited sediments. The deposits were not all thin mud, however. One hummock 225 meters off shore closely resembled a rondel which was the first part of the quay wall to give way.

Apparently the first or mid-afternoon deposit, which accumulated 200–400 meters off shore, overloaded the lake mud. Some of this mud then squirted out from beneath the new load, causing a collapse that produced the waves seen at 6:50 p.m. and started the main slide or flow, which rapidly involved more and more of the lake floor, both shoreward and lakeward. The muzzle velocity resulting from the successive collapses, especially those beneath land, may have been several meters per second, judging by the completion of the land sinking "in a few seconds", but only a meter or two of fall was above the lake level, and so the larger part of the energy propelling the main flow was gained during the descent to the final positions of rest, mostly 30 to 44 meters below the lake surface. When more experimental data on friction in turbidity currents have accumulated, a modified Rehbock energy line may help in analyzing the changes in a combined slide and flow of the Zug type.

Summary

Bed load is to be distinguished from suspended load, but the two are complexly interrelated and, partly for this reason, interpretation of the laboratory data is somewhat uncertain, to say nothing of the applications to natural streams and other currents. We can nevertheless say some things fairly definitely. For example, stream gradient affects velocity, velocity affects competence, and competence may limit load to values far below capacity.

In lakes and seas, turbidity (density) currents may be important agents of erosion and deposition, especially if masses of sediments accumulate at the tops of steep slopes. In a more general sense, all currents in streams, lakes, and oceans are density currents, moving under the compulsion of gravity. The energy involved and its transformations may be represented conveniently by a diagram such as that of Rehbock (Fig. 6).

Despite all the complications introduced by debris transport and a mobile bed, the Chézy and similar formulae have had unquestionable success in predicting the effects of engineering structures, especially for ordinary streams of clear water or those containing only moderate amounts of suspended sediments, under streaming flow. Slope, discharge, channel shape, bed roughness, and velocity actually are interrelated in the general fashion indicated by the formulae. The long-term effects of this interaction upon gradients in different parts of a stream's course are considered in the next section.

The Long Profile

Ideas concerning Graded Profile

Surell (1841) concluded from studies in the French Alps that the elevation at a torrent's mouth is the level to which the torrent's course is adjusted by the growth of an equilibrium slope back up the debris cone and into the mid-course gorge (Fig. 2). Finally the torrent establishes a stable position and adjusted slopes along its whole length. This suggestion of a *profile of equilibrium* was seized upon by the engineer Dausse (1857) and by later geomorphologists and greatly developed.

H. Sternberg (1875) demonstrated that the profile of the middle Rhine, in the sediment-filled graben between Basel and Mannheim, approximates fairly closely to a certain exponential curve (Fig. 9). He considered the effects of increase of water and of changes in the form of cross section, but concluded that the determining factor in the development of the long profile has been the maintenance of the velocities necessary to move the coarsest debris actually found (at 7 points) along this part of the river. He considered that the profile is the

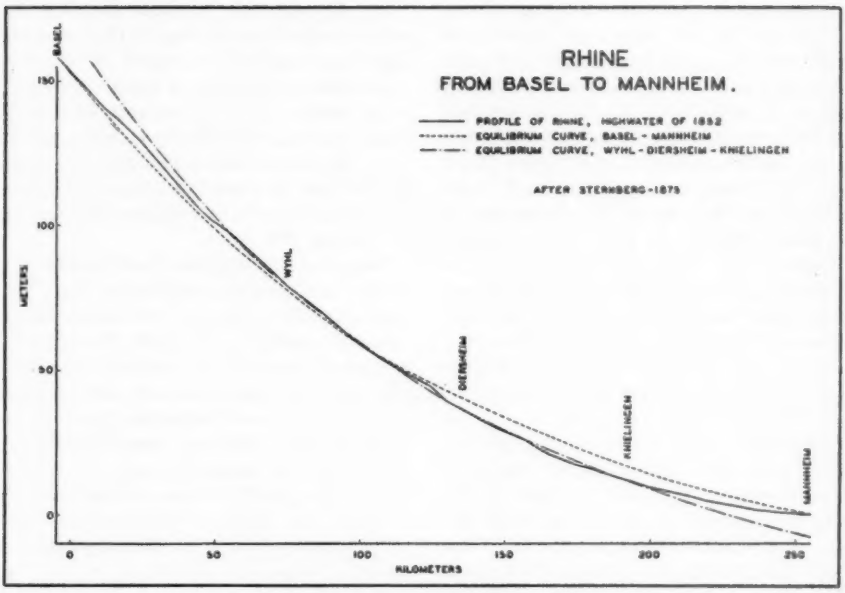


FIGURE 9.—LONG PROFILE OF MIDDLE RHINE
With calculated curves. Vertical exaggeration 1000×

result of the downstream decrease in grain size of the load due to attrition. He was dealing with a special case, a portion of the Rhine that receives relatively little water or debris from tributaries. A somewhat similar case, the Mississippi River below New Madrid, has a somewhat similar long profile (Shulits, 1941, p. 628) and a decrease in coarseness of bed materials from gravelly sand at New Madrid to silty and clayey fine sand below Baton Rouge (U. S. Waterways Experiment Station, 1935, especially p. 124). Sternberg's explanation has been given wide applicability in this century by Central European engineers (Forchheimer, 1930; Schoklitsch, 1937) and by the American Shulits (1941).

G. K. Gilbert (1877), unaware of the work of Sternberg or other Europeans, discovered anew the principles of land sculpture as shown in the Henry Mountains of Utah. He had been impressed by the contrast between the convex structures of the domes and the concave profiles of the radial valleys incised into the domes. In the course of a thorough but non-mathematical analysis, he concluded that increase in quantity of water increases transportation of debris in more than simple ratio. Therefore:

> "The running water which carries the *débris* of a district loses power by subdivision toward its sources; and unless there is a compensating increment of declivity, the tributaries of a river will fail to supply it with the full load it is able to carry" (1877, pp. 109–110).

Erosion is promoted below the mouth of a tributary. Due to the interdependence of slopes[5], the resulting disturbance has secondary effects upstream (erosion) and downstream (overloading, deposition). A concave profile thus results, as the effect of a single tributary. Numerous tributaries, especially if the increase of water therefrom is regular, merely intensify the effect (and perhaps change the form of the curve). Control by baselevel apparently is not necessary. Gilbert emphasized the importance of water volume, Sternberg that of debris size.

Philippson's comprehensive paper (1886) cannot be reported adequately here. He

[5] Fergusson (1863, p. 328) emphasized interdependence of the various parts of the stream flowing on alluvium.

accepted Gilbert's explanation as of chief importance, and in particular minimized the effects of grain size, especially because the load is less when the ultimate curve of equilibrium (the terminant) is approached. In rainy regions, the terminant is flat, in dry regions steep, but

FIGURE 10.—PHILIPPSON'S TERMINANT
MS initial profile. Me 1, Md 2, Mc 3, intermediate profiles. Medcs, terminant.

the two are similar curves. An example—a minor stream in the high Alps—has a gradient decreasing from 74.6 per cent near the source to 10.4 per cent at the mouth. Philippson stated that the Nile, which decreases in water volume downstream, should show a corresponding increase in gradient. The terminant is developed by headward erosion. One special portion of the terminant curve lies above the original surface and hence is imaginary (Fig. 10). The upper part of the original slope will never be eroded. This region makes a zone all around the stream's hydrographic basin. This was considered by Philippson to be the actual condition in many plateau regions, such as the Russian region whose streams were described by von Baer in 1876 as having no upper courses, and the Tsin-ling-shan as described by von Richtofen in 1882. Other possible examples included the Colorado tableland and the western slope of the Sierra Nevada. Philippson did not sufficiently emphasize structural control by flat-lying resistant rocks. Despite the demonstration by Penck (1894) and others that there cannot be a "terminant" profile, and the failure of some predictions—notably that the Nile would be found to have a profile convexity in Lower Egypt—Philippson's paper remains a mine of suggestive information.

Grade and Maturity

History of usage.—W. M. Davis (1902) introduced the term "grade" for the condition of "balance between erosion and deposition, attained by mature rivers" (1902, p. 86). This term was favored as shorter than Dausse's *pente d'équilibre* and more accurate than Philippson's *Erosions-Terminante.*

Davis (1902, p. 86–87) went on to state that:

> "The development of this balanced condition [grade] is brought about by changes in the capacity of a river to do work, and in the quantity of work that the river has to do. The changes continue until the two quantities, at first unequal, reach equality: and then the river may be said to be graded, . . ."
>
> "If any [graded] stream line is followed from head to mouth its profile will show a curve, approximating theoretically to the flatter part of one wing of a parabola; but when studied in detail, the normally continuous decrease of slope downstream is found to be seldom realized. The entrance of a tributary is usually accompanied by a decrease of slope up stream and an increase of slope downstream from the tributary mouth; the spasmodic action of floods introduces some faint symptoms of disorder;"

and the inequalities due to McGee's (1891) *varigradation* are also to be considered (Davis, 1902, p. 93).

> "After a river system has attained a maturely graded condition, it will maintain a graded condition through all the rest of the undisturbed cycle; but it is important to recognize that the maintenance of grade, during the very slow changes in volume and load that accompany the advance of the cycle, involves an appropriate change of slope as well. . . . A large river in a mountain valley may reach grade in the early maturity of its region. It will then flow with a rushing current on a rapidly sloping bed of cobblestones; and it may stand hundreds or even thousands of feet above baselevel. In the old age of the region the same river will flow with a sluggish current on a nearly level bed of sand and slit through a peneplain, only a few tens or scores of feet above baselevel" (p. 95).

W. J. McGee (1891, p. 261–267) stated that in Iowa and elsewhere alluviated meadows form along stream valleys, primarily due to damming by landslides or the fans of tributaries. In time each barrier and then the meadow above is channeled by the stream, leaving terraces. But as long as the new channel is cutting in the barrier it will have a relatively steep gradient, and so a new deposit is formed where the velocity is checked at the lower end of the little gorge. This deposit will in turn be trenched from below, making a series of nicks in the long profile. McGee called this process varigradation, and stated that it is realized in the pools and rapids of every mountain brook, and in great rivers as well. In the Grand Canyon of the Colorado River, where the gradient relationships are those described by McGee,

the controlling factor is quite clearly the immobility of the great boulders of the tributary fans.

Henri Baulig (1926; 1928; etc.) has based his treatment of geomorphology on the equilibrium profile. He has treated the subject qualitatively rather than precisely, considering the morphological criteria and using the results of precise leveling. In particular, he has extrapolated the profiles of undissected or dissected headwater areas as sketched curves that indicate the elevations of the sea at supposed earlier times of stillstand.

Recently, Kesseli has attacked the whole concept of the graded river. According to him (1941, p. 587)

> "balance between the power of a stream and its load is maintained, neither during floods nor during the stages of low water, neither along the entire length of a stream nor along limited stretches, neither in youth, maturity, nor old age."

This statement appears to be based on misconceptions of Gilbert's (and Davis') meaning and of the more careful usages of the terms "load" and "graded" by American geomorphologists.

Mackin (1948) set Kesseli right. He defined a graded stream (1948, p. 471) as

> "One in which, over a period of years, slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for the transportation of the load supplied from the drainage basin. The graded stream is a system in equilibrium; its diagnostic characteristic is that any change in any of the controlling factors will cause a displacement of the equilibrium in a direction that will tend to absorb the effect of the change."

Criteria for graded condition.—Mackin took as one example of a stream at grade a 50-mile segment of the Shoshone River east of Cody, Wyoming. Long maintenance of an average gradient of 30 feet per mile is shown by numerous terraces cut in tilted sedimentary rocks of moderate resistance to erosion. This test is more than acceptable; a single low non-structural terrace at or near the same gradient as the river would be enough, whether the terrace were rock-floored or in alluvium. By this standard the San Gabriel River (Fig. 19) in southern California is graded. Arroyo Larguito (Fig. 12) in the Kettleman Hills of central California, might be considered graded to the first change of gradient upstream from the alluvial terrace (dot-dash line of Fig. 12). The gradient flattens in weak rocks at size sample locality 2, and steepens just upstream. If this nick were due to headward migration, the terrace should be most prominent just below it instead of absent there. More probably the whole undulating profile is in equilibrium, and the narrow upstream shoulders have been completely removed by erosion, so that only downstream terrace remnants remain.

Not all graded rivers are bordered by terraces. When Shoshone River was flowing on the surface represented by its highest terrace it was already at grade. Could its graded condition have been recognized? Under such circumstances, the recognition of a graded stream becomes a matter of individual judgment. Moreover, concave profiles are developed on rocky beds, locally wholly lacking alluvial cover, and the curves are in some cases almost as smooth as those on mobile beds. The courses of the Var, the Durance, and other rivers in southeastern France are in part on rock with a thin gravel veneer, yet the long profiles (de la Brosse et al, 1911–1920) are only moderately undulatory. As will be shown below, steeper stretches downstream are fully as likely to be on gravel as on bedrock.

Change of gradient during maturity.—Davis and all other believers in the mature profile recognize a gradual decrease in gradient as relief is reduced by erosion. Under some circumstances the reduction may be geologically rapid. Possible examples are furnished by streams with fanhead trenches (Eckis, 1928; compare right side of Fig. 12 of present paper) though diastrophism is commonly a possible complication.

Origin of mature profile.—One is tempted to beg the question of profile development by considering all simple concave profiles monogenetic and all compound profiles abnormal, perhaps even rejuvenated. To avoid this prejudgment, we shall consider in some detail the principal known factors in profile development, even at the risk of elaborating some items considered by Mackin (1948).

Volume and Caliber Factors in Profile Development

Volume and caliber have been considered principal factors in determining gradients by both engineers and geomorphologists. For ex-

ample, Baulig (1926, p. 58) stated that "the profile of equilibrium indicates a certain *rapport* between four variables: discharge, velocity, the mass of the load, and its caliber". We should add at least one other factor, form of cross-section. But we find a sharp difference of opinion as to the relative importance of the factors which determine stream gradients, especially in a stream's middle and lower course where it is travelling chiefly or entirely on a mobile bed made up of debris it has itself transported. What has here determined stream gradients: the volume of water, the size and character of the debris, some other factor, or a combination of two or more factors? According to Gilbert's analysis, the quantity of water is the decisive factor; according to Forchheimer and other followers of Sternberg, the quantity of water and the form of cross-section are significant factors but pebble size is the chief determinant of gradient.

The upper Danube and its tributaries, especially its major tributary, the Inn, furnish a crude but useful test (Putzinger, 1920). The profiles of the Inn and Danube Rivers are reproduced as Figure 11, together with equilibrium curves calculated from Sternberg's formula. The Danube and Inn have approximately the same volumes. If Gilbert were correct, we might expect that the gradient below the junction would be flatter than for either stream above the junction. Actually,

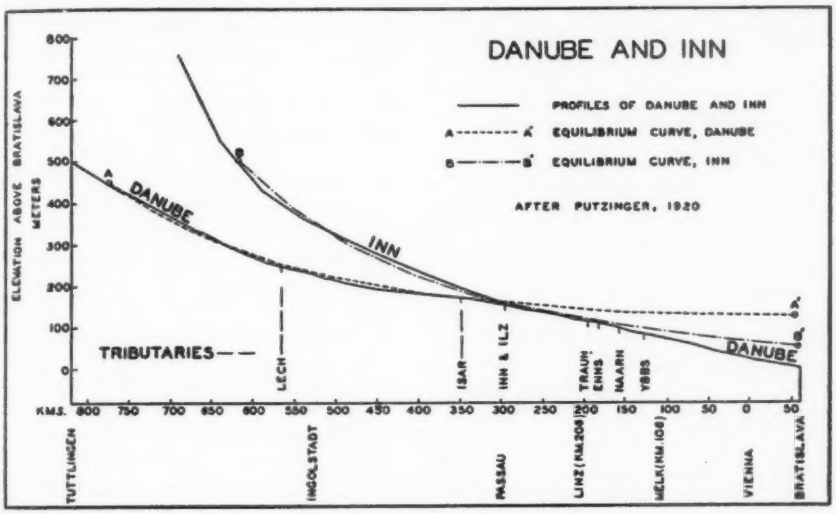


FIGURE 11.—LONG PROFILES OF DANUBE AND INN
Vertical exaggeration 500×

below the mouth of the Inn, the Danube's gradient steepens and closely fits the calculated equilibrium curve of the Inn. Still steeper gradients below the mouths of the Traun, Enns, Naarn and Ybbs may be due to coarse debris introduced by these minor tributaries. Either Sternberg's debris size factor is actually the controlling one or the analysis has not been sufficiently comprehensive. Fugger and Kastner (1895) after study of 26,000 pebbles from six localities on the Salzach, a major tributary of the Inn, concluded that in the Alpine rivers cobbles are not worn down, but cracked up. Sternberg's coefficient of wear is therefore probably not directly applicable to an Alpine stream.

Putzinger's test was not entirely satisfactory, because neither pebble sizes nor discharges nor hydraulic radii were reported. It is difficult to obtain all these data for any stream system anywhere. Fairly complete information has been published for the French Alps (de la Brosse et al., 1905 et seq.), but without any data on sediment sizes. Neither do the French reports give much information concerning cross

FIGURE 12.—LONG PROFILE AND SEDIMENT SIZES OF ARROYO LARGUITO, CALIFORNIA
Transit stadia survey by Edward Taylor. Vertical exaggeration 10×

sections. Professor Edward Taylor of Pomona College in 1938 tried to get information concerning sediment sizes on the Danube and Inn, and along the Var and Isère in the French Alps. The snows of winter and the floods of spring aggravated the inherently difficult sampling problem. His results did indicate, however, that below the Inn-Danube junction at Passau the coarse gravel of the Inn becomes the dominant element in the load of the Danube, as shown by the excavations of gravel companies in the river bed.

Smaller drainage lines are easier to deal with. As one example, take Arroyo Larguito, a small ravine whose waters have their source in the Kettleman Hills of central California and flow southwestward onto Kettleman Plain (Canoas Creek Quadrangle) (Fig. 12). This dry water course is considered mature, as it is cut in weak materials, has numerous concordant tributaries, and has the usual equilibrium profile, concave upward and roughly paralleled by a low terrace. If the profile was determined by debris size, we might expect the sediments now strewn along the ravine to be coarse at the head and finer at the mouth. The size variation diagram (Fig. 12) shows, on the contrary, that the sediments are relatively fine-grained at all points, with some increase, especially in maxima, below a conglomeratic zone. For this ravine, debris size seems to have been immaterial. Perhaps quantity of water controlled gradients.

These two examples, one a great river, the other a small ravine, produce a feeling of uncertainty as to the relative importance of debris size and stream volume. Perhaps a more general statistical study is needed. As an initial contribution, Figures 13 and 14 show the discharge-gradient relationships at gaging stations in the French Alps (data from de la Brosse, 1905–). The slopes used were mostly for short stretches of 0.2 to 2.0 kilometers, taken from detailed stream surveys, with horizontal distances to 10 meters, elevations to 0.1 meter. The discharges were means of 1 to 12 maximum monthly means, in liters per second, commonly for May or June, years 1905–1917. Figures 13 and 14 show that in general flat gradients and large discharges go together. The empirical curves $SQ^{1/2} = k$ where S stands for slope, Q discharge and k 1.5 or 2, fit the data fairly well. Figure 13 represents 73 gaging stations, many of which are on rocky stretches. Figure 14 represents the 32 stations on alluvium, and here the scatter is distinctly less. The lack of data on sediment sizes makes impossible any comparison between the effects of discharge and debris size on gradients, at the mouths of tributaries or elsewhere.

Bedrock and Alluvial Gradients

A stream with steep and varying gradients on bedrock throughout its upper course is immature in its upper course, and also considered as a whole. A stream regularly increased by tributaries, with a uniform or uniformly increasing veneer of alluvium on bedrock in its upper course, and with a regularly decreasing gradient downstream, would probably be in equilibrium and fulfill Mackin's (1948) definition of the graded stream.

A smooth gradient curve is not, however, a requisite for equilibrium. The Rhine has a slight hump in its profile opposite the Kaiserstuhl, below Basel and just above Wyhl (Fig. 9). This hump was tentatively explained by Sternberg (1875, p. 501) as the result of a buried buttress of Kaiserstuhl bedrock. No available evidence indicates that the equilibrium of the unregulated Rhine was less perfect here than in other parts of the Rhine graben. In general, equilibrium rather than profile smoothness is the test for maturity. Unfortunately the equilibrium condition is harder to determine.

Form Factor; Effect of Gorges and Broad Alluviated Stretches

The effects of channel characteristics on the long profile have been discussed by Sternberg (1875) and Mackin (1948, p. 483–490), among others. Sternberg calculated the optimum form of cross-section for a regulated stream designed to prevent the formation of bars at all stages of water by keeping the hydraulic radius constant. Mackin emphasized the common increase in gradient, demonstrated by several California workers, where a stream leaves a mountain gorge to spread out upon a broader alluvial surface. Eckis (1928) has also treated this special case in some detail. An exceptionally

FIGURE 13.—DISCHARGE-GRADIENT GRAPH FOR SEVENTY-THREE STATIONS, FRENCH ALPS
Dashed line, $SQ^{\frac{1}{2}} = 2$

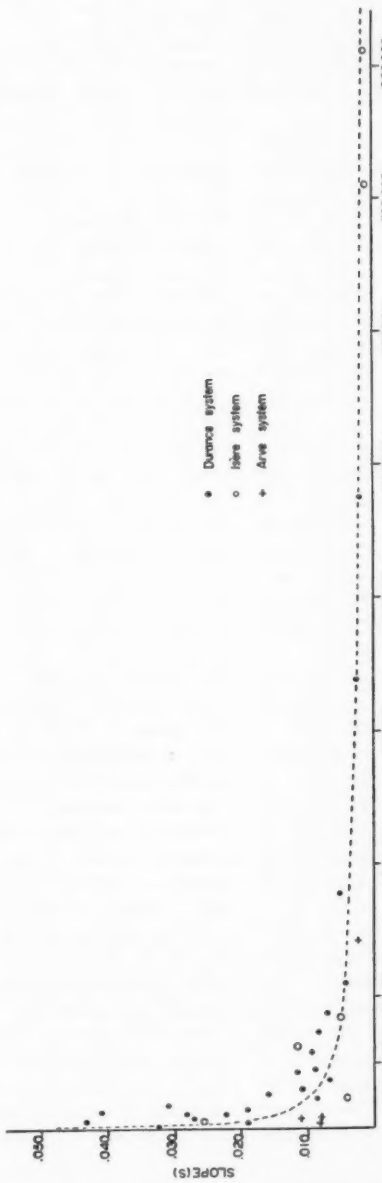


FIGURE 14.—DISCHARGE-GRADIENT GRAPH FOR THIRTY-TWO STATIONS ON ALLUVIUM, FRENCH ALPS
Dashed line, $SQ^{1} = 1.5$

large increase in gradient was shown by Yuba River after the period of hydraulic mining, from 0.10 per cent (5–6 feet per mile) in the Sierra gorge to 0.34 per cent (16–20 feet per mile) on the alluvial slope (Gilbert, 1914, p. 135; 1917, p. 53, 62).

The phenomenon is not limited to California. Oldham (1888) described alluvial fans on the Indian plains, near Hardwar and elsewhere, with trenches cut into the lower part of the fans at gradients less than those on the fan surface. The Patthri Rao near Hardwar, where confined on a superpassage over the Ganges Canal, had a depositional gradient of 14.5 feet per mile, dropping to 3.04 feet per mile where the stream was allowed to spread out and then increasing after 220 yards to 20.3 feet per mile on the surface of the fan.

The general problem is not a simple one. The shape and position of the main channel may be more significant than the cross-section of the whole river (Mackin, 1948, p. 489). Islands are complicating elements, especially the numerous islands of a braided stream. Along many large rivers there are repeated sudden changes from a narrow channel in a gorge to a broad or braided channel in an alluvial basin, and then back again to a gorge. Is anything similar to fanhead steepening found in the alluvial basins? This possibility demands attention.

Dausse (1857) was impressed by the effect of channel shape upon the erosive power of the regulated Isère and other streams in southeastern France. He also stated that one of these streams, the Durance, has flatter gradients in gorges than at the heads of the succeeding debris cones.

Penck (1891) stated that the Danube, which traverses a series of alternating gorges and basins, uniformly has flatter gradients in the gorges. In the case of the Hungarian plain below Pest (Penck, 1891, p. 36), the steeper gradient may be in part due to a decrease of water volume. Fugger and Kastner (1895) studied the Salzach, a member of the Danube system which passes through seven basins, with narrows between. According to their profile the gradient usually steepens at a narrows, but in one short gorge it is flatter. Putzinger's 1920 profiles (Fig. 11) suggest that the Danube itself has a steeper gradient in the gorges below the mouth of the Inn. Obviously the Danube is a complex case, with more than one factor involved.

Exner (1925), in the course of a mathematical analysis of the interaction between water and debris in streams, reached the conclusion that a stream erodes wherever it narrows and deposits where it becomes broader. Dausse's proposition is a possible corollary. Excellent data are now available on one of Dausse's original examples, the Durance (Fig. 15). The uppermost gorge between basins, about 280 km. from the river's mouth, is 3.3 km long and very rocky. Its gradient ranges from 6.4 per cent at the head to a minimum of 1.6 per cent, with a mean value of 3.2 per cent, much steeper than any gradient downstream. Apparently an equilibrium slope has not been attained here. In the next long gorge, above Sisteron and 160–175 km from the river's mouth, the bed is alluvial and the 0.27 per cent gradient is almost exactly the same as that of the braided stretch above and the unbraided stretch below Sisteron, almost to the mouth of the Bléone. Here the narrower unbraided stream, either in or below the gorge, has shown no increased erosive power, or else compensation has occurred. Below Sisteron there are no long gorges, but a marked general steepening of the gradient from the mouth of the Bléone to Mirabeau (0.34 per cent) and then a flattening to 0.24 per cent between Mirabeau and the Rhone. Perhaps the steepening above Mirabeau should be correlated with a series of narrows, though these are not pronounced. In short, Dausse's case is not clearly proved by the more recent data on the Durance. Actually, excluding the immature, glaciated stretch near the source, this river's long profile seems closely related to discharge, which in turn is roughly proportional to hydrographic basin area (Fig. 15).

The correlation between gradient and shape of cross section indicated by hydraulic data is hard to find for large, accurately surveyed, unregulated rivers. The effect may well be there but in the cases studied it is masked.

Meander and Valley Axis Profiles

The lower Mississippi River, between Cairo and the Gulf, has a meandering course that in 1926 was about 1090 miles long. At a much

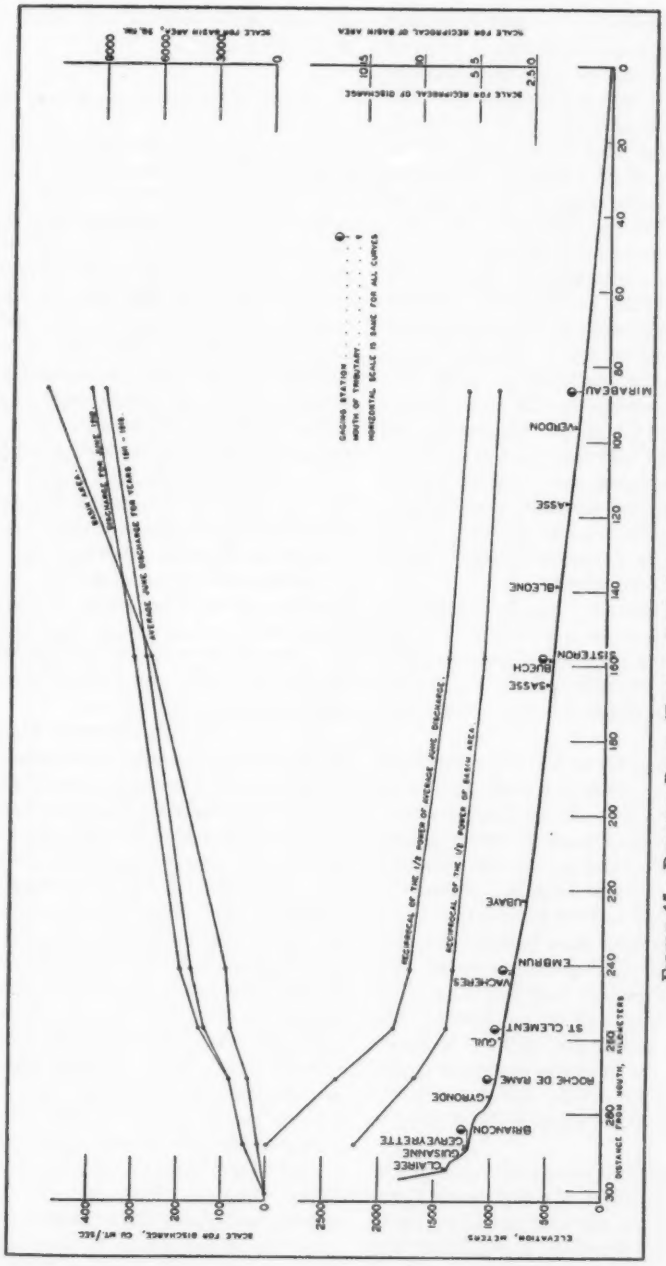


FIGURE 15.—DURANCE RIVER (FRENCH ALPS) GRADIENT AND DISCHARGE CURVES
Vertical exaggeration 30×

earlier date, perhaps in the latest Pleistocene (Fisk, 1944), the river followed a series of braided courses, each set of braided channels being 4 or 5 miles wide and probably about 600 miles long. The braided courses were relatively short, first, because the Gulf probably extended to a point west of New Orleans, and second, because the braided channels were approximately parallel to the valley axis. The mean gradient was 0.5 or 0.6 foot per mile.

The cause of meandering has been investigated experimentally at Vicksburg (Friedkin, 1945). The Mississippi's meandering probably commenced when the supply of debris-charged glacial melt waters slackened or ended. The meandering Mississippi had its mean gradient reduced to about 0.3 foot per mile, but handled its reduced load with ease, and even cut its flood plain to a slightly lower valley-axis gradient. In general, the initiation of meandering flattens the gradient of a river's lower course, and so produces a concave profile without requiring erosion anywhere.

The present courses of the Mississippi and other large meandering rivers are more or less stabilized by the tough mud in their natural levees. Even more resistant to erosion are the thicker clay plugs filling cut-off meanders (Fisk, 1947).

The Mississippi has reacted somewhat slowly to the numerous artificial cut-offs made since 1929. The length of the river was reduced 151.8 miles by 1948 (mimeographed circular, Mississippi River Commission; *see also* Ferguson, 1938), and the mean bank-full gradient increased from 0.29 to 0.335 feet per mile. Actually bed adjustments have been so slow that the profile is undulating, steeper in and near cut-offs than elsewhere. Gage heights at flood have been reduced 5 or 10 feet, however, and velocities are presumably slightly increased. Surely in time the river will become entrenched slightly above the cutoffs, and the entrenchment will extend upstream to Cairo and beyond.

On an unregulated stream that meanders in a flood plain, the effects of cut-offs on gradients appear to be slight and transient. If the whole lower course of the river is considered, the increase of stream length by the growth of meanders more or less balances the reductions through cut-offs, and the total length remains about the same.

Is Base Level Necessary for Mature Profile?

Gilbert (1877, p. 124) derived the concave profile directly from the succession of gradient adjustments caused by the junction of any two streams. Numerous tributaries, especially if the increase of water in the principal stream is regular, merely smooth out the effect. Control by base level apparently was not considered necessary. Gilbert's conclusion has been challenged by Challinor (1930), who agreed with Bain (1897, p. 433–476) that repeated increases in quantity of water should cause accelerated corrasion downstream, resulting in a convex profile if an effective base level is not present.

If a stream plunges over a cliff, shooting flow develops just above the falls, and the stream's velocity increases in the section where shooting flow prevails. A corresponding increase in erosion seems probable, and also a gradual extension of the whole series of effects back from the falls, up the stream. Thus, even without increases of water from tributaries, the lower course of a stream deprived of base level might become convex upward.

The actual profiles developed above falls, along hanging tributaries, or above fault scarps in several widely separated parts of the world are shown in Figure 16. In all cases convexities are present, but they do not extend far upstream. The examples are chosen to show the range of variation. Little is known about the geology of the African example. The Rhine crosses its filled preglacial valley just above the Rheinfall, and has re-excavated the preglacial valley below the falls. Yosemite's Cascade Creek (Fig. 16C) shows a convexity between 5300 and 5700 feet elevation, developed since Matthes' (1930) mountain valley stage, and two slight undulations downstream, probably indicating two later stages of relative stillstand: Matthes' canyon stage and the present period of control by the level of Yosemite Valley (Matthes, 1930, pl. 27). Yosemite streams passing over falls (not represented here) have convexities similar to that above the Rheinfall. The California and Rhine convexities, and probably the African also, are in

FIGURE 16.—LONG PROFILES ABOVE SCARPS

A and C from U. S. G. S. maps; B from Gillman (1932), pl. 2; D, plane table survey; E from Anon. (1889), pl. 5. Vertical exaggeration: A, 5×; B, 20×; C, 2×; D, 20×; E, 500×.

hard rock. Another set of examples, cut chiefly in hard rock, are the more or less hanging tributaries of Kern River, in the Sierra Nevada south of Yosemite, whose profiles were prepared by Melvin Swinney in the course of the present study, but have been published by Webb (1946, pl. 5).

A similar convexity has developed in the weak sediments of San Antonio alluvial fan east of Claremont, Los Angeles County, California (Fig. 17). It was formed by erosion and deposition upstream and downstream from an artificial scarp, during and immediately after the great flood of March 2 and 3, 1938. Maximum discharge was probably 3000 or 4000 second-feet (Troxell *et al.*, 1942, p. 224). In a little more than 24 hours, a trench up to 16 or 18 feet deep was cut, extending headward 2500 feet from the scarp; this trench was then partially filled with coarse bouldery alluvium so similar to the enveloping sediments that the contact can be found only with difficulty. After the flood the new long profile was a fairly smooth curve, convex upward in the vicinity of the former scarp. On a vastly larger stream, the Mississippi, the somewhat similar but much flatter New Madrid convexity may possibly have been initiated by earth movements associated with the 1811 New Madrid earthquake, and preserved at least temporarily by slight differences in caliber of bed load (U. S. Waterways Experiment Station, 1935, p. 124).

Why do convexities occur instead of sharp nicks? How far upstream will the effect of the initial convexity be felt? These questions are hard to answer at best, but may be handled somewhat better after consideration of the process of rejuvenation of a stream controlled by base level. First, however, we mention briefly the mathematical formulation of the profile curve.

Mathematical Expression for Mature Profile

Galileo (quoted by Baulig, 1926) suggested that the longitudinal profile approaches the form of a quarter circle. Grandi (quoted by Baulig, 1926) proposed as a more accurate substitute the arc of a cycloid. Tylor (1872) suggested that many great rivers, including the Ganges, approach a parabolic curve, but that in a few cases a hyperbola gives a closer fit. Sternberg (1875, p. 490) proposed for the Rhine between Basel and Bingen the exponential (logarithmic) curve $y_1 = y \frac{1-e^{\lambda/4\lambda n x_1}}{1-e^{\lambda/4\lambda n x}}$, where x_1 and y_1 (and x and y) are the horizontal and vertical coordinates, respectively, of points on the curve, λ (a small fraction) is a function of pebble size and resistance to wear, and n has the value 2 or 4. Curves calculated from this formula are shown in Figure 9. Dünkelberg (1878, quoted by Philippson, 1886) and I. C. Russell (1898) favored the cycloid, Lake (1928) the catenary. Exner (1922) suggested on theoretical grounds not connected with pebble wear that an exponential curve $y = C_1 + C_2 e^{(-\gamma x)/k}$ is approached. This is somewhat like Sternberg's equation. Here x and y are the horizontal and vertical coordinates of a point on the curve and k, C_1, and C_2 are constants. O. T. Jones (1924) proposed for the upper part of the Welch river Towy the empirical logarithmic curve $y = -k \log (x + a) + b(x + a) + c$, where x and y are the horizontal and vertical coordinates of a point on the curve, and a, b, c, and k are constants. A. A. Miller (1939) critically restudied Jones' calculations and reached the conclusion that two other logarithmic curves fitted Jones' data better. Miller pointed out the need for caution in the extrapolation of profile curves. Green (1934; 1936) showed that a simplification of Jones' curve, namely $y = a - k \log (p - x)$, a, k, and p being constants, fitted a portion of the upper Towy very well and was also useful in synthesizing fragmentary stream terraces in southeastern England. The application of the equation to the upper part of a Thames tributary—the Mole—and to a set of terraces along the lower Mole (Green, 1934, p. 56) was especially satisfactory.

Almost all these mathematical expressions for the curve are empirical. Obviously a given set of constants applies only to a single river or even to only a portion of a river's course. The greatest value of the calculated curve is for comparisons between different parts of the same stream, or between a stream's present course and terraces downstream or at higher levels.

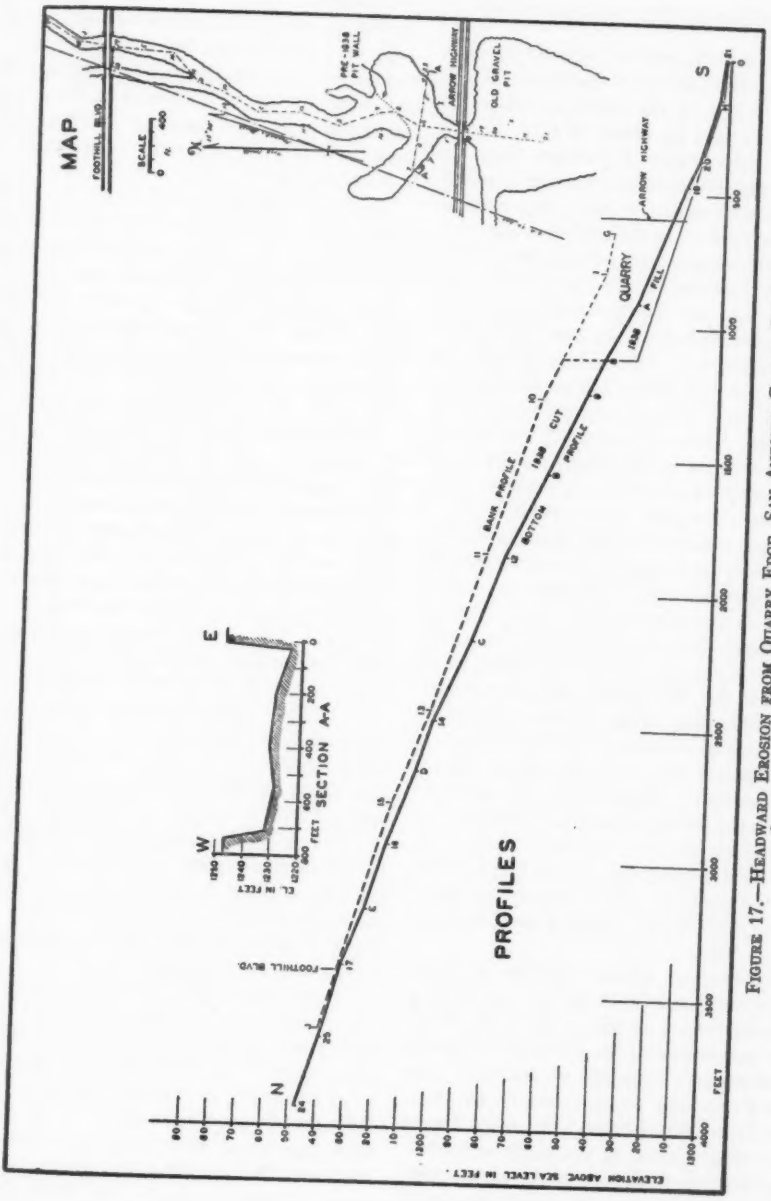


FIGURE 17.—HEADWARD EROSION FROM QUARRY EDGE, SAN ANTONIO CREEK, CALIFORNIA
Survey by Edward Taylor. Vertical exaggeration 10×

Profile Changes Following Rejuvenation

Nickpoints and convexities in uniform materials.—The valley-in-valley relationship is well known. By one of the oldest postulates in geology (presaged by Steno, 1669, p. 30) the narrower inner valley is younger than the larger topographic form into which it is incised.

If the larger valley is a mere gully, carrying little or no water, then the headward migration of the inner valley is well marked, and the long profile of the valley as a whole shows a pronounced nick. In the semi-arid portions of southwestern United States, headward migration of gullies is aided by rodent burrows and other shallow passages in soil or mantle rock. The little intermittent streams tend to go underground above the nickpoint and emerge below. Somewhat similar conditions appear to prevail along some of the small chalk rivers in southeastern England (Green, 1934).

In larger streams, or those working on less permeable uniform materials, a nick is replaced by a profile convexity. Examples have been given in a preceding section (Fig. 16). No exceptions to this rule were found in the course of this investigation. The rule is based, however, on so few field studies, and those mostly in California, that as an inductive generalization it must be considered very tentative.

How quickly may a newly formed nick or falls in uniform material become a mere convexity in the profile? In one day, in the case of the flood on the San Antonio debris cone, described in the previous section. For resistant rocks, the rate of erosion is of course very much slower, though wholly pertinent direct evidence is not at hand.

Nick-points on resistant portions of varied rocks.—O. T. Jones (1924, pl. 44) has published accurately leveled profiles of the Welsh River Towy and several of its tributaries. Marked nickpoints occur especially on the Towy just above Fanog and on its tribuary Pysgotwr above Troedyrhiwruddwen. The sharp breaks in the profiles come at the heads of narrow gorges cut into hard rock of the lower "grey mudstones" of Silurian age, which apparently forms an effective local temporary base level. At least part of the numerous nickpoints found by Baulig (1928) in his detailed and well documented study of the *plateau central* of France are similarly localized on resistant rock. Baulig considered geological structure and rock resistance in a general way but apparently concluded that for his purposes, and especially for the determination of a series of general base levels due to eustatic changes of sea level, the geographic or geologic position of a nickpoint was unimportant.

Dated inscriptions or structures are associated with a few rapids on resistant rock in such a way as to suggest the rate of erosion. Ball (1903) collected impressive but not conclusive evidence that the silt-laden Nile cut down 26 feet into the resistant gneiss of the Semna cataract in 4200 years. The profile nick indicated by the rapids has not been entirely eliminated and its position has not moved.

Upstream progression of nicks caused by cut-off meanders.—Macar (1934) presented evidence suggesting that the rapid produced in a cut-off channel through a meander neck has in many entrenched valleys migrated upstream, in three cases as much as 5, 9, and 15 miles, respectively. I have restudied more than half of Macar's examples, using the same U. S. Geological Survey and Belgian topographic maps; two profiles with 16 of his 72 cases are shown in Figure 18. The restudy appears not to justify the conclusions reached by Macar. There are fewer rapids than cut-offs, and individual rapids are not obviously paired either with single cut-offs or with groups of cut-offs. Spring Creek, a tributary of Wolf River (Fig. 18) shows a striking nickpoint near its mouth, but the drop is so great as to raise doubt as to the competency of the cut-off as a cause. Macar did not adequately study the local geology for his U. S. examples. The nicks may have been due to causes not considered by him.

Natural and artificial cut-offs for which accurate records are available do not aid much toward settling the question raised by Macar. Other types of regulation go along with both types of cut-off and obscure the issue. Since 1929, cut-offs have reduced the length of the Mississippi River below Cairo from about 1090 to about 938 miles. The 1947 gradient curve shows a slight convexity just below Cairo, centered on New Madrid, but most of the lower river, including all the cut-offs, still shows a fairly smooth concave profile with minor local steepening at each cut-off. For the

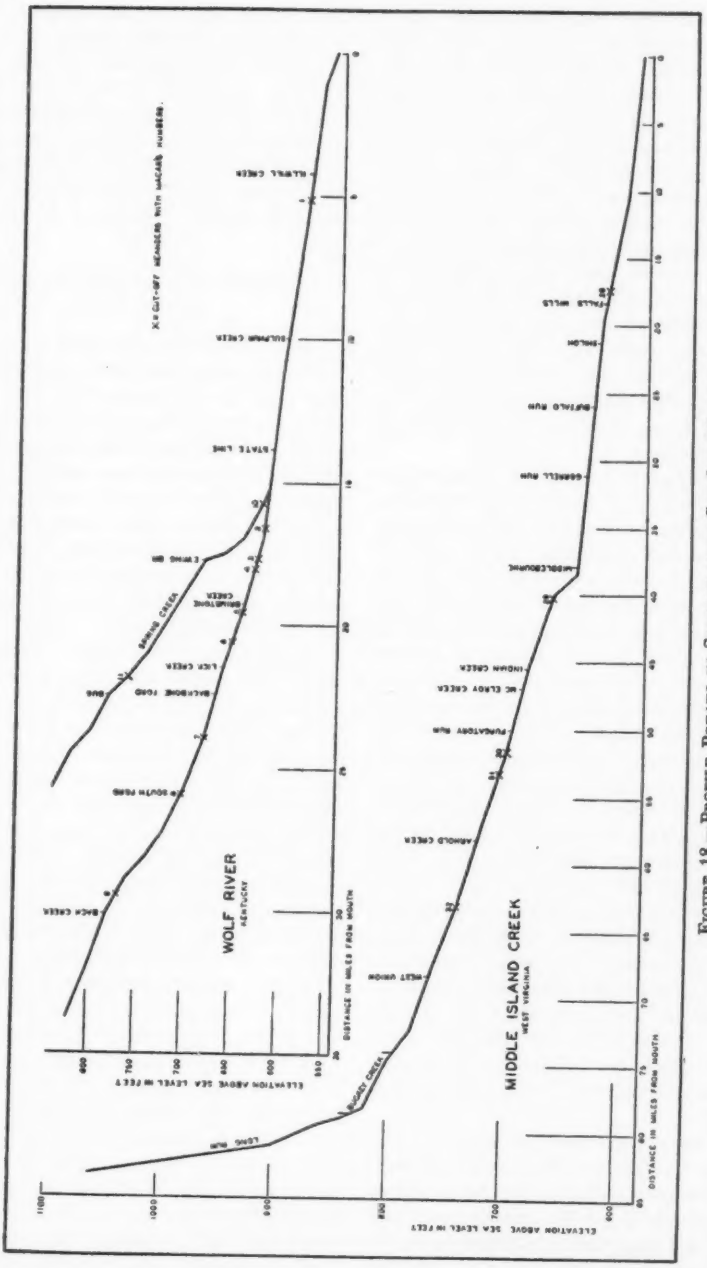


FIGURE 18.—PROFILE BREAKS IN STREAMS WITH CUT-OFF MEANDERS

first 420 miles below Cairo the average gradient is 0.45 feet per mile, for the next 270 miles 0.35 feet per mile, and for the last 320 miles, on the delta, 0.03 feet per mile. Peak heights for the great 1937 flood were the highest on record at Cairo, but below Memphis and especially in the intermediate 0.35-foot gradient reach, they were as much as 12 feet below expectations on the basis of previous records. Nevertheless cut-off steepenings have been maintained. In general, high water profiles have been steep just above the cut-offs, relatively flat just below. At the 1937 low-water stage, gradients at cut-offs were mostly between 0.50 and 1.20 feet per mile. Erosion of barriers, mostly stiff clays deposited in old ox-bows or other still places, has been slow, even though aided by dredging.

Theoretical analysis of nick migration.—Lehmann (1936) concluded that a step or nick in a long profile can be preserved during migration upstream in rock of uniform resistance, if there is shooting flow and no erosion in the stretch above the retreating nick. Otherwise the nick does not last. Even in the rare case of shooting flow for a stretch of several kilometers, if there is downward erosion upstream, the nick will be eliminated in the course of a very few kilometers retreat. Rough estimates indicate that if headward erosion is 20 times the downward, a 200-meter nick will be eliminated in some 4 kilometers of retreat. Lehmann's observations on Swiss streams indicated that with streaming flow, or shooting flow plus erosion, a nick is transformed into a flat sigmoid curve, which decreases in prominence as it moves upstream. Sycamore Creek, near Riverside, California, a rejuvenated stream (Fig. 16D), appears to show the sigmoidal inflections which Lehmann considered the most probable result of rejuvenation. One or more such inflections might be transformed into a sharp nick at a point where the rock becomes notably more resistant upstream.

Significance of rejuvenation profiles for Gilbert-Bain uncertainty.—The existence of short convexities above falls, and the transformation of falls and rapids into flat smooth profile convexities, are important considerations in the handling of geomorphic problems, but their bearing on the Gilbert or Bain-Challinor analyses of profile development is not clear. Base level may or may not be necessary for the formation of a concave profile. A probable prerequisite for a conclusive demonstration is a precise quantitative evaluation of all the factors, assuming increase of water volume at a constant rate or by regularly spaced increments. However that may be, equilibrium profiles (if they exist at all) actually are formed under the control of sea level or local base levels.

Geographical Distribution of Mature and Immature Profiles

General distribution.—It might be supposed that shield, shelf, and other relatively rigid areas would be the regions where the cycle of stream erosion has reached maturity, whereas the circum-Pacific and Mediterranean-Himalayan belts of Alpine and later folding would be characterized by immature profiles. On the contrary, studies of stream profiles show that the areas of stream immaturity have little if any relation to these grand divisions of the earth's surface. Perhaps the most widespread and notable examples of immaturity are to be found in central and southern Africa, where many river profiles are broken by falls and rapids. The tributaries of the Congo and the Zambezi have made relatively slight inroads upon the plateau of eastern Angola (Beetz, 1930). The Nile waters are first gathered into Lake Victoria and then pass over falls and through gorges, lakes, and broad marshes, en route to Egypt and the Delta. In North America, the Adirondack Mountains form a striking example of immaturity which is only in small part directly due to glaciation. The Raquette and other tributaries of the St. Lawrence have made only moderate progress in excavating valleys with smooth gradients in the domed bulk of the Adirondacks.

California Coast Ranges.—Central and southern California, though in the circum-Pacific belt, have many mature streams. In the San Gabriel Range east of Los Angeles the larger streams, notably the San Gabriel River and its major tributaries, have smooth long profiles far into the range, and flow on alluvial beds 50–75 feet thick, whereas minor stream systems, for example the Cucamonga, are marked by falls and rapids and extremely irregular though roughly concave long profiles (Fig. 19).

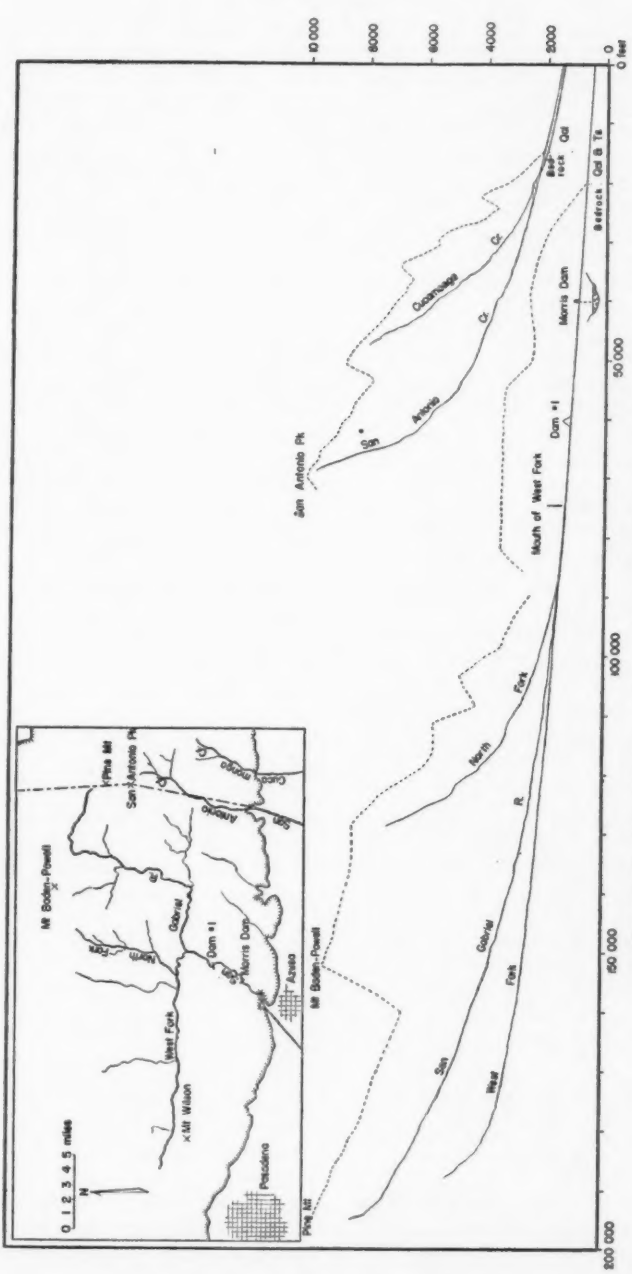


FIGURE 19.—LONG PROFILES IN SAN GABRIEL MOUNTAINS, CALIFORNIA
From U. S. G. S. maps. Qal, alluvium; Ts, Tertiary. Vertical exaggeration 5×

The San Gabriel gravel has been studied statistically by Krumbein (1940). Gravel terraces are present, even along Cucamonga Creek, up to several hundred feet above the middle and upper stream courses. The San Gabriel River gradients are about 60 feet per mile (1.1 per cent) in the lower canyon, steepening to 65 or 70 feet per mile (1.3 per cent) on the alluvial fan at the head of the lowland course. These gradients are higher than the corresponding ones for some other small mature southern California rivers.

Close relationship between stream size and maturity of profile is also shown by the Kern River and its tributaries in the Sierra Nevada (Swinney, *in* Webb, 1946, pl. 5).

Summary: Stream Gradients

The gradients of mature streams in a single region are approximately inversely proportional to a function of their discharges (Fig. 13), but are also affected by other factors, such as varying resistance to erosion (Fig. 9, vicinity of Wyhl), debris sizes (Fig. 9), and perhaps also channel form. The mature long profile of a stream increased by tributaries commonly, but not always, approximates a smooth curve, which may be formalized as a logarithmic curve with different constants for each case. Deviations from the calculated curve (e.g., for the Danube below the mouth of the Inn) demand explanation, and so become aids to an understanding of the geomorphic conditions or in deciphering the geomorphic history. Rejuvenation, as by vertical uplift of the whole region, may cause a sharp initial nickpoint, which in weak materials is quickly transformed into a smooth convexity but may be reformed at the downstream edge of a band of rock so resistant that it establishes a local base level.

Salinas Land Valley and Monterey Sea Valley

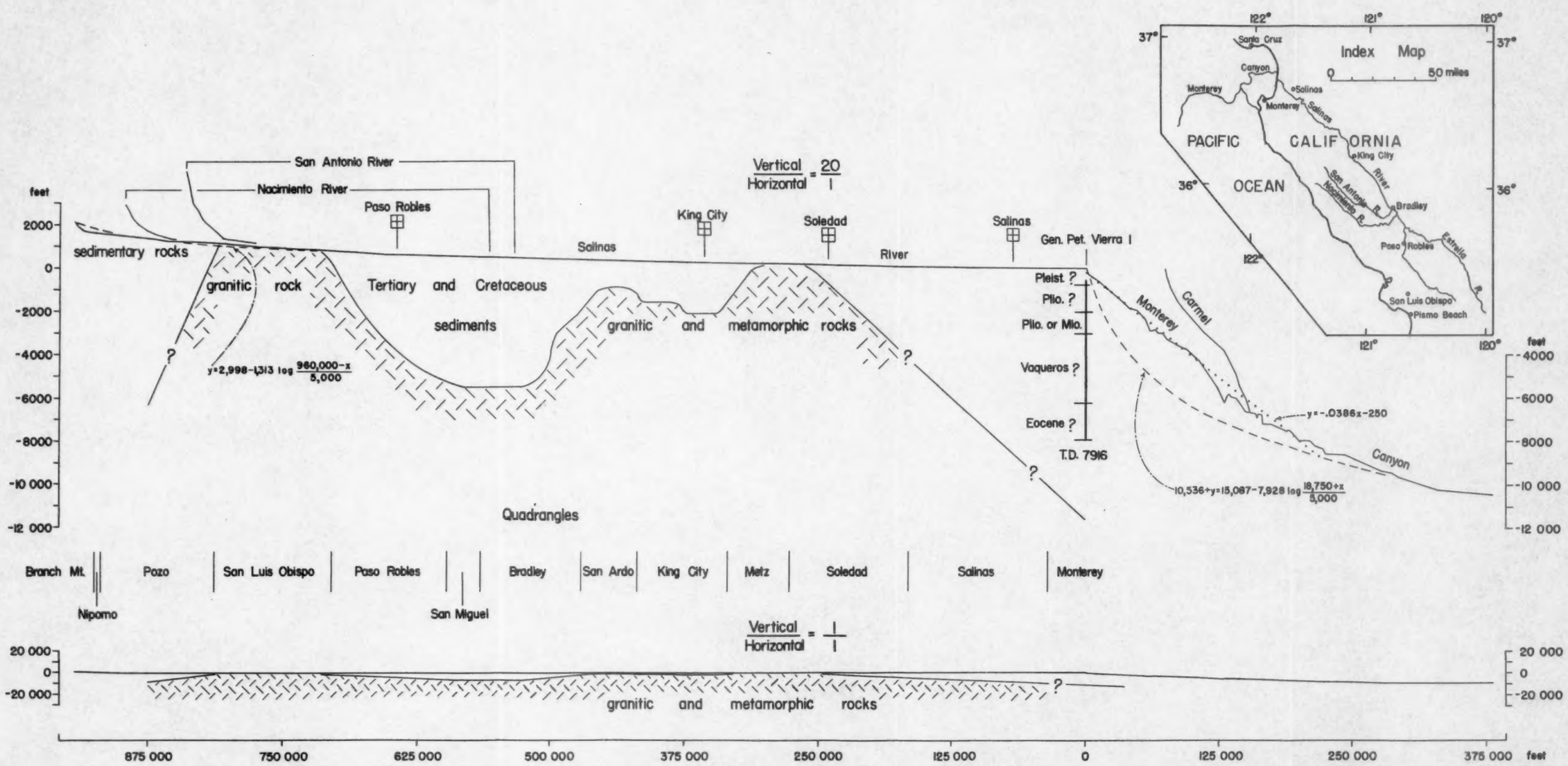
Long Profiles

As an application of the accumulated knowledge concerning stream gradients, consider the Salinas Valley of central coastal California and its apparent prolongation as a deep canyon beneath the waters of the Pacific Ocean. The canyon, called the Monterey submarine canyon by Shepard and Emery (1941), is a sea valley of unusual size, comparable to the major Sierra Nevada canyons in depth, width, and average gradient. Salinas Valley trends N. 45° W. between the Santa Lucia Range (and Sierra de Salinas) on the southwest and the Gabilan Range on the northeast. Monterey submarine canyon extends west and then southwest from the mouth of Salinas Valley.

The long profiles of Salinas River and Monterey Canyon are shown in Plate 1. The course and elevations for the Salinas were taken from the current editions of the 1:62,500 maps of the U. S. Army and U. S. Geological Survey. The first 5 miles above the mouth might perhaps better have been taken from Hamlin's (1904) plate 2 to show the pre-1908 discharge through Elkhorn Slough (MacGinitie, 1935; Beard, 1941). This was not done because the slightly decreased length of the present river was not considered significant. It may be worth noting that repeated summer damming of the present outlet since 1908 has resulted in minor early winter discharges through the Elkhorn exit (MacGinitie, 1935). Monterey sea valley heads off Moss Landing, less than a mile south of Elkhorn Slough. The data for the sea valley are from U. S. Coast and Geodetic Survey unpublished charts. The upper part of the profile for Carmel submarine tributary is based on Shepard and Emery's survey (1941, Pl. 7). The submarine soundings, especially those by fathometer, are less reliable than land elevations, and so the details of the sea valley profile are somewhat uncertain. Perhaps the closed depressions are not real.

The long profile of Salinas River is a fairly smooth curve, close to $y = 2998 - 1313 \log \frac{960{,}000 - x}{5{,}000}$, where y is the elevation in feet and x the distance from the mouth in feet. The curve would not be greatly different if the profile along the valley axis were substituted for the stream profile. The equation is modelled on Green's (1936).

Salinas River flows to the sea in winter but is dry for much of its length in summer. The maximum measured flood discharge was about 75,000 second-feet, recorded at Hilltown bridge near Salinas, 12 miles from the mouth, Febru-



LONG PROFILES OF SALINAS RIVER, MONTEREY SEA VALLEY, ETC.
(SOLID LINES) AND CALCULATED CURVES (DASHED AND DOTTED LINES)

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ary 12, 1938. The average discharge here, 1930–1947, was 627 second-feet (Paulsen, 1949, p. 172), but this value has relatively little meaning because of the very small discharges between May and October, and the large year-to-year variations. The maximum discharge during 1947 was only 268 second-feet. The average annual discharge at Hilltown bridge, 1926–1945, was 476,500 acre-feet (Simpson, 1946, p. 61).

The river flows on a mobile bed for most of its course. Sand and grit are the predominant bed materials, with fine gravel fairly abundant. A bed sample collected in August, 1947, near Atascadero, at $x = 700{,}000$, in one of the few stretches not dry at that time of year, yielded the following mechanical analysis:

>16 mm. diameter	24.6%
8–16 " "	16.5
4– 8 " "	7.2
2– 4 " "	17.8
1– 2 " "	19.2
½– 1 " "	8.4
< ½ " "	6.2
	99.9%

Hasty inspection of stream bed and gravel pits at various localities indicated that this sample was representative of the portion of the stream's course between $x = 750{,}000$ and $x = 250{,}000$, though the variations are considerable. The sediment becomes finer near the river's mouth. There is no obvious effect of caliber of load on gradients.

The relatively minor deviations of the actual profile from the calculated curve are almost entirely above Atascadero ($x = 700{,}000$), and may be owing to two causes. First, the steep headwaters slope, above $y = 1{,}850$ feet, may indicate that an oversteepened tributary was chosen instead of the shorter, beheaded main stream. Second, the shallow gorges with bedrock walls between $x = 725{,}000$ and $x = 825{,}000$ (Fairbanks, 1904) mark a slight hump in the profile, even though these gorges are themselves choked with sand and gravel.

Monterey sea valley is a deep canyon which for most of its course has a V shaped cross-section. It heads just off shore near Moss Beach and extends at least as far as the foot of the steep continental slope, a distance of 70–75 miles, where its floor is about 10,500 feet deep. Maximum depth beneath the nearest parts of the gently sloping continental shelf is 4800 feet, 23 miles from the valley head and 6 miles from the nearest land at Point Pinos near Monterey, California. The principal tributaries are Carmel Canyon, from the left or south side, and Soquel Canyon from the north side.

The gradient of Monterey sea valley is much steeper than that of the land valley, and the long profile does not resemble closely any logarithmic curve. In fact, for the first 225,000 feet from the head of the sea valley, extending somewhat beyond the junctions with Carmel and other major tributaries, the smooth curve that most closely approximates the profile of Monterey sea valley appears to be a straight line with 3.86 per cent grade, $y = -.0386x - 250$ (Pl. 1), where y is the depth, in feet, and x the distance from the valley head, in feet. Note that the first half mile has a much steeper gradient, about 11.5 per cent. For comparison, the logarithmic curve $10{,}536 + y = 15{,}087 - 7928 \log \frac{18{,}750 + x}{5000}$, passing through 0 and 10,536 feet depth, is also shown in Plate 1. This curve is similar to that for Salinas River, with the steeper average gradient of the sea valley. It is fairly close to the profile of such a Sierra Nevada valley as the Middle Fork of American River, but obviously very unlike the actual profile of Monterey sea valley.

Geomorphology of Lower Salinas Valley

Salinas Valley is 8 or 10 miles wide at its mouth, 7 miles wide at Salinas 9 miles from the sea, and 5 miles wide at Soledad about 35 miles from the sea. Above Soledad, the valley floor narrows gradually but irregularly to a width of 1000 feet at Wunpost 93 miles from the sea; above that point it is sharply reduced to a width of 200 feet.

Erosional and depositional terrace surfaces, in part marine, are present northeast and southwest of the mouth of Salinas Valley. On the northeast side, a well marked alluvial terrace is about 15 feet above the river. A more extensive river and coastal terrace is commonly

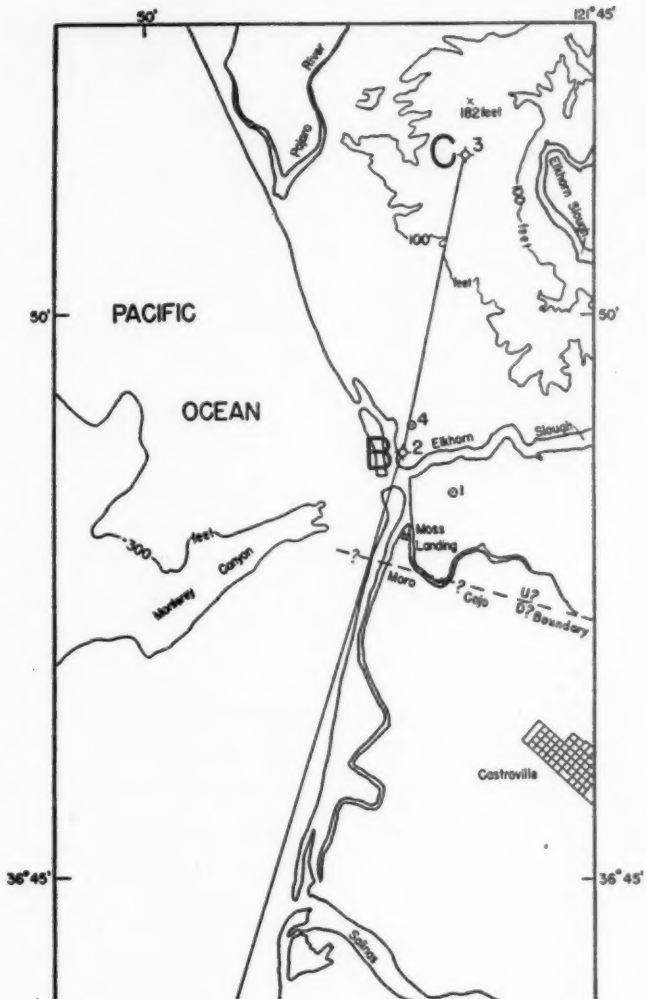

FIGURE 20.—MAP OF MOUTH OF SALINAS VALLEY

1. Vierra water well; 2. General Petroleum Vierra No. 1; 3. Western Gulf Johnson No. 1; 4. Western Gulf Watsonville No. 16.

about 100 feet above the sea, but may rise to 150 feet elevation just beyond the north end of the section of Figure 20. At this point it is topped by ancient sand dunes rising to 180 feet

elevation (Beard, 1941). The 15- and 100-foot terraces can be traced only a few miles up Salinas Valley, though stream terraces appear again 40 or 50 miles inland, near King City, 100 feet or more above the river. The apparently warped terrace north of the mouth of Salinas River suggests differential crustal movement with the axis of Salinas Valley depressed, or lagging behind the uplift of its northern border.

Subsurface geology of lower Salinas Valley

The general structure beneath lower Salinas Valley suggests one possible factor in the origin of Monterey submarine canyon. Lower Salinas Valley is a structural basin (Lawson, 1893; see also Fig. 21). Granite or similar plutonic rock, exposed at the surface southwest and northeast of the valley and only about 2800 feet below sea level at the north end of the section of Figure 21, is at least 7916 feet deep beneath Moss Landing on the northeast side of the basin, and presumably even deeper beneath the Valley axis. Miocene, Pliocene, and Pleistocene rocks fill the bedrock trough, with pre-Miocene sediments perhaps present in the deepest central portion. Not all formations thicken troughward. The upper Miocene Monterey organic shale (Galliher, 1931; Bramlette, 1946), which has been estimated to be 3100 feet thick (Galliher, 1931) at its type locality just southwest of Salinas Valley's mouth, is much thinner or possibly even absent from the lower Salinas (Monterey Bay) basin. Marine Pliocene sediments are present beneath the Valley's mouth, though not as thick as in a trough northeast of Salinas Valley (Allen, 1946). Perhaps all Pliocene and early Pleistocene sediments beneath the Valley's mouth are marine, though the continental, upper Pliocene to Pleistocene Paso Robles formation, which filled many valleys or other depressions in all the earlier rocks, is as much as 1100 feet thick in upper Salinas Valley, and is present in the hills southeast of Monterey.

The Paso Robles and all earlier rocks are overlain unconformably by the probably late Pleistocene and Recent alluvium of lower Salinas Valley. A general geologic map, such as that of California published by the California Division of Mines in 1938, suggests the possibility that at Soledad, 35 miles from the sea, the late Quaternary alluvium lies directly on granite and other old crystalline rocks, without intervening pre-Quaternary sediments. This is definitely the case on the northeast side of the valley, where the Salinas River now flows just east of Soledad. It is possible, however, that the King City fault (Schombel, 1943) along the southwest side of the valley drops down a wedge of relatively weak Tertiary sediments which has been followed by the river and covered by the river's broad alluvial fill. The contours on the top of the basement prepared for upper Salinas Valley by Bramlette and Daviess (1944), if modified to fit the depth of 2440 feet to basement rock in Chanslor-Canfield-Midway Oil Company's Salanco No. 1 well and extended northwest to the vicinity of Soledad, might indicate a maximum of 2000 feet of Tertiary above the granite southwest of Soledad. The extrapolation is very uncertain, however.

Gray alluvium of Recent (and late Pleistocene?) age is probably thickest at the river's mouth, with a gradual decrease upstream (Pl. 1). According to Simpson (1946), the trough sediments of lower Salinas Valley down to 500 or 600 feet depth are mostly similar to the surface alluvium, but with layers of blue clay confining two well-marked artesian horizons centered at about 180 and 400 feet depth, respectively. Beard (1941, and personal communication, July 4, 1947) has reported marine shells (abalones?) in the blue clay at about 165 feet depth, as far inland as Salinas (Pl. 1). The artesian waters are in hydraulic equilibrium with the sea water off shore, as shown by the rapid invasion of salt water following the lowering of the water table a few feet below sea level by excessive pumping (Simpson, 1946). The two artesian water gravels are poorly defined or missing north of the Moro Cojo groundwater boundary which extends inland from the submarine canyon head along the north side of the valley.

The relationship between the latest gray alluvium and the older alluvium—in part gray and unweathered, in part reddish and of upper Pleistocene age (Taliaferro, 1943)—is somewhat complex. Marginal topographic discor-

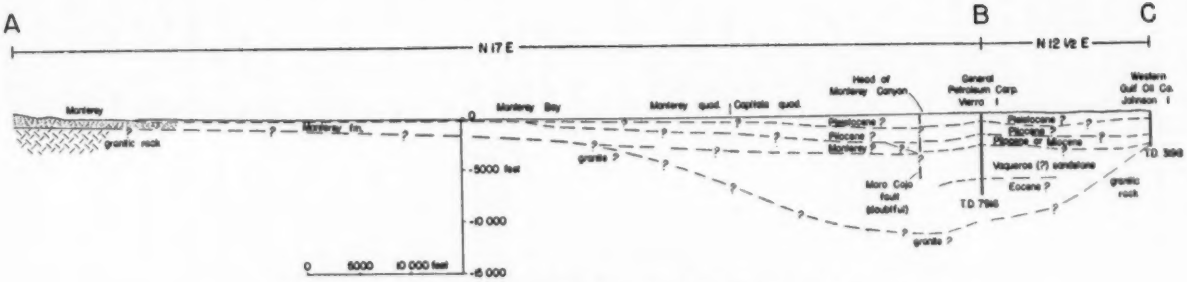

FIGURE 21.—STRUCTURE SECTION ACROSS MOUTH OF SALINAS VALLEY, CALIFORNIA
See Figure 20 for positions of B and C

dances against risers and terraces near Castroville, and against truncated older fans on the southwest side of the valley, suggest Recent valley fill in a broad, shallow trough, perhaps extending to about 200 feet below present sea level, to the base of the upper water gravel. However, the total thickness of late Quaternary alluvium in the Valley's mouth (the Pleistocene? of Fig. 21) may be 750 feet. Almost the last change of sea level or diastrophic event recorded in the area is that which caused the river to cut down (possibly 200 or 400 feet) into the old alluvium. The very latest eustatic change of sea level (or diastrophic event) resulted in the valley fill and the flooding of such shallow estuaries as Elkhorn Slough.

Three wells closely grouped on the north side of the Moro Cojo line, near the submarine canyon head, give evidence as to local peculiarities of the Quaternary alluvial fill, and some idea of the thickness of the underlying Tertiary sediments. These wells are General Petroleum Corporation's wildcat well Vierra No. 1, Western Gulf Oil Company's Watsonville core hole No. 16, and the A. T. Vierra deep water well (Figs. 20, 21).

The Vierra water well has a log unlike that of most water wells in the lower Salinas Valley (Table 2). Notable is the blue clay from 140 to 575 feet. The usual water gravels at 180 and 400 feet were not found. Shell fragments from a point several hundred feet (probably 813–816 feet) deep in this well, given to Dr. C. Noble Beard by Mr. Vierra and determined by Professor U. S. Grant IV, included *Olivella biplicata*, *Schizothaerus nuttalii*, and *Saxidomus nuttalli*, all Recent shallow water species (0–20 fathoms, Burch, 1946). A change of base level is indicated, probably previous to the latest valley cutting.

Western Gulf Oil Company's Watsonville No. 16 and General Petroleum Corporation's Vierra No. 1 were only 1300 feet apart, just north of Elkhorn Slough and Moss Landing (Fig. 20). The log of Watsonville No. 16 (Table 3) is unlike that of the A. T. Vierra water well but even less like that of the usual lower Salinas Valley water well, in that no water gravel was found at 180 or 400 feet. Both wells are north of the Moro Cojo groundwater boundary (Fig. 20; Simpson, 1946). This boundary may be a fault, or it may merely be the north edge of the late Pleistocene valley.

TABLE 2.—DRILLER'S LOG OF A. T. VIERRA WATER WELL

Half a mile northeast of Moss Landing
Surface elevation 40 feet

feet	
0–5	soil
5–40	sand and clay
40–135	sandy mud
135–140	gravel and sand
140–575	solid blue clay
575–780	gray soft shale
780–792	blue sand
792–794	blue clay
794–802	clay and gravel
802–810	blue-green sand
810–813	hard sandstone
813–816	sea gravel and shells
816–817	gray clay
817–829	gravelly sand
829–831	light gray clay
831–835	conglomerate, sand, and boulders
835–868	green-blue tight sand
868–886	yellow clay
886–895	blue-green clay
895–897	white sand
897–903	blue clay
903–906	gravel
906–910	hard blue clay
910–916	sticky clay
916–926	gravel with 10 inches hard sandstone
926–941	soft green sand
941–943	hard shelf sandstone
943–976	soft sandstone
976–979	dark hard clay
979–983	sand, gravel, and shale
983–995	dark hard clay
995–999	blue shale

The logs of Western Gulf's Watsonville No. 16 (depth 1157 feet) and General Petroleum's Vierra No. 1 (depth 7916 feet) were used in the preparation of Figure 22, showing the tentative base of the late Quaternary marine and alluvial sediments at 745 feet depth. Pliocene and Pleistocene sediments are at least 2000 feet thick in Vierra No. 1, perhaps much more. The section between 1500 and 2000 depth is almost certainly marine Pliocene, on lithologic grounds and the presence of marine mollusca and foraminifera. Below the Pliocene are 900–1000

feet of brown Pliocene or Miocene shale, underlain by 1600–2000 feet of pebbly sandstone, perhaps Vaqueros Miocene in age.

TABLE 3.—SUMMARY OF CORE RECORD OF WATSONVILLE NO. 16*

Depth	Core recovery	Description of cores
0–93 feet	0 feet	[No samples]
93–380	41	Gray silt, clay and sandy silt; some shell fragments and wood.
380–621	180	Dark green fine sand
621–655	28	Gray clay and silt; some shell fragments.
655–690	27	Brown sand, sandy clay and (at 684') gravel made up of Monterey (upper Miocene) shale, sandstone and limestone fragments ("Vierra's fresh water horizon", presumably equivalent to the 794 or 813 foot depth in the A. T. Vierra water well).
690–735	25	Brown to green clay and silt, with some limestone nodules.
735–745	5	Brown sand with white pebbles (Monterey shale?)
745–790	31	Brown to greenish gray silt and silty sand; some tan limestone nodules and some hard sandstone.
790–935	64	Gray, brown and green sand and sandstone; some quartz and other pebbles and boulders; 10–12 feet of interbedded tan to dark-gray silt and clay.
935–1040	87	Interbedded green, blue, and gray clay, silt and fine sand; in part hard and compact; limey nodules in basal sandy clay.
1040–1157	84	Dark-gray (or green or brown) fine sand; ½-inch micaceous peat at 1122 feet.
1157 Total Depth		

* Drilled in 1931 from an elevation of 4 feet. Copy of Western Gulf Oil Co.'s complete core record at Pomona College, Geology Pamphlet No. 4912.

If the younger sediments dip very gently seaward, there must be at least 2000 feet of relatively soft Pliocene and Pleistocene fill just off shore, though the Pliocene (?) does contain some hard sandstone beds below 745 feet, judging from Western Gulf's Watsonville No. 16 log.

Origin of Submarine Valley Head

With the geology in mind, we may go back to Plate 1 and consider the origin of the submarine valley head. Obviously this valley head is not just a submerged portion of Salinas River valley, because of its steep gradient of 11.5 per cent for the first half mile, and approximately 4 per cent for the next 45 miles, in contrast to the 0.06 per cent grade of lower Salinas Valley.

Giving up the hypothesis of simple submergence, one might suggest that the Salinas-Monterey profile, with its pronounced nick-point at the ocean's edge, is just what one would expect if, before Monterey Canyon time, base level had been at its present position, and then was dropped a mile or two, initiating the cutting of Monterey Canyon. But it has been shown above that streams large and small, upon rejuvenation, develop compound curves, convex at the "nickpoint", concave above and below. A convexity develops if the rejuvenated stream cuts down into materials of uniform resistance, whether weak or strong. In the sands, gravels, and sandy clays of Salinas Valley headward erosion should have been rapid, and slopes of 11.5 per cent, or even 4 per cent, non-existent or evanescent.

The improbability of rejuvenation as an explanation of the discordance between the Salinas and Monterey profiles becomes apparent if we consider what would happen if sea level should now be lowered suddenly a mere 300 or 400 feet. At the next Salinas River flood of 10,000 or 20,000 or 30,000 second-feet, the water would pour into the exposed Monterey canyon head. It would roll down the 11.5 per cent slope with high velocity, at least 20 feet per second, probably much more. If the water

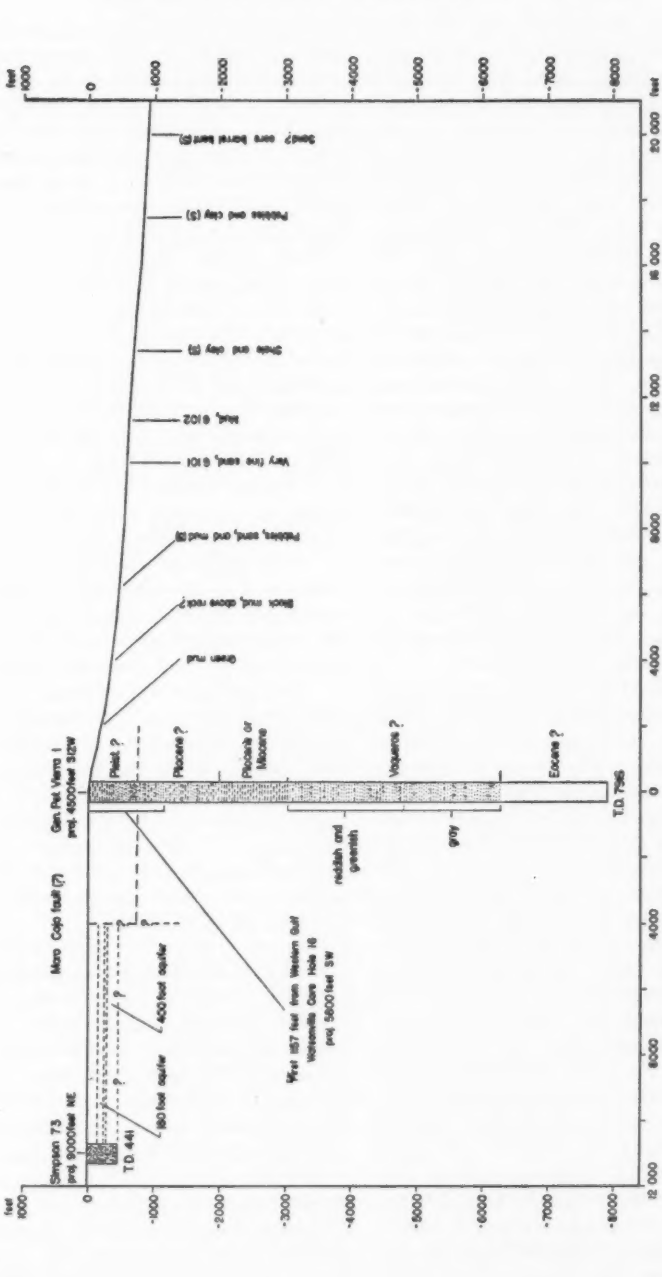

FIGURE 22.—SECTION ALONG LOWER SALINAS VALLEY AND UPPER MONTEREY SEA VALLEY

Water well Simpson 73, from Simpson (1946). Bottom samples: (S) or unmarked, Shepard and Emery (1941); G101 and G102, Galliher (1932); Vertical exaggeration 2×.

depth were less than 12 feet, shooting flow would develop, with further increase of velocity (*see* section on Types of flow, under Hydraulic factors). The alluvium at the canyon head would probably melt away as rapidly as did that of San Antonio Creek, Los Angeles County, in 1938 (Fig. 17), or the silt and sand along New River when the Colorado flowed into Salton Sea during 1905–1907 (MacDougal, 1917, p. 463). Headward erosion from the Monterey canyon head would probably be at the rate of hundreds or thousands of feet per flood season. The nickpoint could not persist at, or anywhere near, its present position, or maintain anything like its present prominence.

Another conceivable origin for the shore-line nick in the Salinas-Monterey profile would be by downwarping or downfaulting of the submarine portion. Inspection of Plate 1, supplemented by study of the Coast and Geodetic Survey charts, failed to suggest any combination of folding, faulting, and subaerial erosion that would produce the present submarine topography. A more general consideration of valley drowning by downwarping will be found later in this paper.

The head of Monterey Canyon is incised into the Pleistocene (and Recent?) fill at Moss Landing. There is no suggestion of deltaic or estuarine deposition in the shape of the canyon head, which comes up practically to the shore at Moss Landing. This part of the canyon must therefore be as late as or later than the fill. (*See* Steno's Postulate no. 3, year 1669, p. 30.) If the fill is older, the canyon head is a subaerial or submarine erosion feature. If contemporary, then the canyon must somehow have been kept clear while a wall of mud and sand was forming alongside it.

Elkhorn Slough, just north of the canyon head, with a maximum depth of 18 feet (MacGinitie, G. E., records at Hopkins Marine Station, Pacific Grove, California), is the barely drowned mouth of the abandoned course of San Benito River (Allen, 1946). It was apparently out of action as a river course at the time of lowered base level when the Salinas Valley 180- and 400-foot water gravels were deposited. It may be suggested tentatively that the Elkhorn course was abandoned by San Benito River in pre-Wisconsin time. The almost complete absence of water sand or gravel from the upper 780 feet of the A. T. Vierra water well indicates probable pre-Wisconsin (or at least pre-water gravel) age for these sediments. Elkhorn Slough, at the mouth of a short beheaded drainage system, may have been considerably deeper than its present 18 feet in Würm-Wisconsin time, but it was probably a narrow, short hanging valley nonetheless.

There is some uncertainty about the character of sediment in Monterey Canyon or sea valley down to 400 fathoms (2400 feet). Galliher (1932; 1935) showed silt and clay covered by 1–4 cm of gravel and sand from 450 fathoms to 300 fathoms (2700–1800 feet), silt and clay from 300 fathoms up to 100 fathoms (1800–600 feet), very fine sand from 100 to 18 fathoms (600–108 feet), and fine sand from 18 fathoms to the shore. Galliher found biotite largely altered to glauconite below 50 fathoms on either side of the axis of Monterey Canyon, and emphasized the slowness of deposition indicated by the presence of glauconite. Shepard and Emery (Table 4) found along the axis "hard bottom out to depths of 5000 feet. Sand frequently stuck to the core barrel, or the core nose was bent in, indicating rock or at least gravel bottom. . . .The findings of this investigation appear to be quite different from those made by E. W. Galliher" (Shepard and Emery 1941, p. 91).

Shepard and Emery's table 3 (1941, p. 92) copied here as Table 4, summarizes their data on bottom samples from the axis of Monterey Canyon. Approximate distances from the canyon head have been added.

The two surveys are in approximate agreement at 2643 feet (440½ fathoms). Shepard and Emery suggested rock floor at 1015, 2095, and 2117 feet and rock beneath mud at 340 feet, because no cores were recovered or the coring devices were damaged. From Figure 22, it is apparent that at 340 feet depth, 3400 feet from shore, hard rock bottom is extremely improbable, and compacted Pleistocene or Recent sand perhaps the most probable material, beneath the soft coating of mud picked up by the dredge.

In summary, the plan of the upper part of Monterey Canyon suggests that it is the drowned continuation of Salinas Valley, but the other known features are either nondiag-

nostic or indicate that the two valleys have had different origins. The steep-sided cross profile of the sea valley might be explained as the result of the subaerial rejuvenation of the certainly Recent in age, incised in sediment which may be late Pleistocene and Recent. All things considered the canyon head must be of late Quaternary submarine origin.

TABLE 4.—SAMPLES TAKEN ALONG THE AXIS OF MONTEREY CANYON BY SHEPARD AND EMERY (1941)

Depth (ft.)	Approximate distance from canyon head, ft.	Sample character	Sampling device	Notes
200	1,900	Green mud	Snapper	
340	3,400	Black mud	Snapper	
340	3,400	None	Ekman Corer	Valve broken by impact, suggesting rock beneath mud cover
480	6,500	Pebbles, sand and mud	Dredge	
690	14,000	Shale and clay	Dredge	
840	16,500	Pebbles and clay	Dredge	
900	17,500	Sand on outside	E–D corer*	Core barrel bent
1015	20,500	None	E–D corer	Core barrel broken from valve indicating probable rock
1980	50,000	Sand	Dredge	
2095	52,500	None	E–D corer	Nose nicked and core barrel bent suggesting rock
2117	53,000	None	E–D corer	Same as above
2643	60,000	Pebbles and clay	Dredge	
3850	93,000	Sand and silt on outside	E–D corer	Core fell out
4800	106,000	Brown mud	Snapper	
5040	108,500	Gradation from cobble on bottom up through gravel, coarse sand and mud on top. 17-inch core.	E–D corer	
6200	120,000 to 133,000 (45,000 NW of Pt. Pinos light).	4-ft. 9-in. core, silt with sandy layers. More sandy underneath	E–D corer	

* E–D corer is the heavy coring tube devised by Emery and Dietz.

Salinas River, if that explanation were compatible with the other characteristics of the upper part of the sea valley. But the long profile of the upper sea valley is too steep to fit the Salinas curve and its slope is too uniform for the upper part of an independent subaerial drainage line. The tremendous profile change between lower Salinas River and the submarine canyon head is on weak alluvium rather than at the downstream edge of hard rock. In such material, a smooth and gentle convexity in a compound subaerial profile would be expected, rather than a sharp nick. The uppermost part of the Canyon is almost

The Monterey canyon head merges into the rest of the gorge without any break except the change of gradient at 250 feet depth. Nevertheless the problem of the origin of the whole sea valley cannot be discussed adequately without first giving some consideration to the other sea valleys along the California coast and their probable origins.

OTHER SEA VALLEYS OFF CALIFORNIA

Distribution and Gradients

Shepard and Emery (1941) have given convenient names to 27 of the more or less canyon-

like valleys off the California coast, including all those of large size (Table 5). Tributaries, named or unnamed, are relatively rare, though several canyons are like the Monterey in having two or three or four. Long stretches, including the 120 miles between Lucia and Arguello Canyons, appear to lack sea valleys.

Gradients are as steep as or steeper than that of Monterey Canyon. Shepard and Beard (1938, p. 441) found mean gradients of 2.9 per cent for Monterey and two other canyons, higher means—up to 12.5 per cent—for a dozen others. The mean of Shepard and Beard's gradients for 15 California canyons is 5.7 per cent. The northern canyons, cut into the continental slope, mostly show deep outer trenches incised in the slope, and a marked gradient convexity near the top of the slope (near the outer edge of the continental shelf). Monterey Canyon extends deeply across the whole shelf

TABLE 5. DATA FOR CALIFORNIA SEA VALLEYS
Compiled from Shepard and Emery's Charts I–IV (1941)

North to South	Depth at head	Depth at mouth	Remarks
	feet	*feet*	
Trinidad Valley	3900 poorly marked	7,800?	Marked convexity below −4800 feet, shallow valley above −4800 feet
Eel Canyon	300–600	8,400	Marked convexity below −5100 feet
Mendocino Canyon	300	9,000?	Poorly marked mouth, near a scarp
Mattole Canyon	300 or less	—	Tributary of Mendocino
Spanish Canyon	<300	vague; ? at 3,300 ft.	? Trib. of Delgada
Delgada Canyon	shore	10,200?, vague	
Noyo Canyon	600	10,500	
Bodega Canyon	600?	10,500? very vague below 9000	
Pioneer Canyon	900 far from shore	9,300 or deeper	
Ascension Canyon	600	7,500?	
Soquel Canyon	300	—	Trib. of Monterey
Monterey Canyon	shore	9,300	Mouth in "Monterey trough"
Carmel Canyon	shore	—	Trib. of Monterey
Sur Canyon	300	10,000±	Marked confusion in midcourse
Partington Canyon	shore	—	Poorly coordinated, Sur trib.
Lucia Canyon	300	7,000±	Very shallow in midcourse
Arguello Canyon	600	11,400	Very shallow in upper part; 2 tribs.
Hueneme Canyon	shore	1,800	Empty into undrained basins.
Mugu Canyon	shore	1,800–2,100	
Dume Canyon	shore	1,800?	Empty into Santa Monica Basin
Santa Monica Canyon	300	2,100	
Redondo Canyon	shore	1,800	
San Pedro Sea Valley	300	2,700	
Newport Canyon	shore	1,200?	Very Shallow
Catalina Canyon	300–600	3,000	
La Jolla Canyon	shore	2,700?	Empties into San Diego trough
Coronado Canyon	300	4,000	Empties into San Diego trough

and so lacks this distal convexity. The southern California sea valleys, from Hueneme south, are smaller inshore features, whose mouths are in the basins that characterize that portion of the sea floor. Of the 27 submarine valleys named by Shepard and Emery, only 7—Eel, Mattole, Noyo, Monterey, Sur, Hueneme, and Newport—head close to the mouths of streams large enough to be called rivers. Five others—Carmel, Mugu, Santa Monica, San Pedro, and Coronado—are fairly close to possible discharge points for the Carmel, Santa Clara, Los Angels, and Tia Juana rivers, respectively. The other 15 have no relation to rivers. Though 11 California rivers are fairly near sea valleys, 12 California rivers—from north to south, Smith, Klamath, Mad, Russian, Sacramento-San Joaquin, Santa Maria, Ventura, San Gabriel, Santa Margarita, San Luis Rey, San Dieguito, and San Diego—have no corresponding sea valleys or canyons. The Pajaro, San Lorenzo, and Santa Ynez rivers are doubtful cases.

As pointed out by W. S. Tangier Smith long ago (1902, p. 671), most California sea valleys head abruptly at or near the shore line, but they have "mouths" at widely variable depths. The only valley heading at depth is the far northern Trinidad. Another exceptional case is that of Pioneer Canyon which heads 20 miles from shore at 600–900 feet depth. The "mouths" fall into two groups, those at 1200–4000 feet in the closed basins off southern California, and those at 7000–11,400 feet north of Point Concepcion, the latter all well down on the continental slope.

Subsurface Geology near Valley Heads

Considering the sea valleys as a group, four difficulties face the thorough-going subaerialist: (1) the steepness of the mean and valley head gradients; (2) the failure of sea and land valleys to join; (3) the absence of gorges between the southern California basins or between the basins and the floor of the deep Pacific beyond the continental slope; and (4) the fact that not a single California canyon heads in an estuary. The heads are at or outside the general coastline. The lack of estuaries is especially noteworthy in areas deeply filled with weak, late Tertiary sediments, especially Salinas Valley, Ventura Basin, and Los Angeles Basin. Study of Los Angeles Basin (Poland, 1947) indicates maximum Recent valley fill of 140 feet for any trench through the low coastal ridge at the southwest margin of the basin. Even adding 100 feet for the height of the uptilted coastal ridge, only 240 feet is indicated for the depth of the Recent or latest Pleistocene valley cutting.

Elsewhere along the California coast, the depths of valley fill suggest varied lowerings of sea level in Wisconsin time. Perhaps the best evidence is that collected by Upson (1949) from wells in Santa Ynez land valley just north of Point Concepcion. Here the base of the alluvium indicates the probable long profile of the Santa Ynez River at a relatively recent time of lowered sea level. Extending this profile seaward, Upson estimated that sea level was 300 feet lower in late Wisconsin time than at present.

It appears that almost all the California sea valleys are in one respect the opposite of land valleys—they have their heads instead of their mouths nearly at sea level. The suggestion is strong that present sea level is for them the controlling horizon, and that at least their upper parts have been formed by submarine processes, probably in late Pleistocene and Recent time.

Selected Atlantic Sea Valleys

Mississippi Sea Valley

Three sea valleys off other coasts than California are described to supplement the data already given. One of these, that off the Mississippi delta, appears to have an exceptionally important relation to a filled river valley. The Mississippi sea valley or trough heads in the continental shelf about 60 miles west of the mouth of the Mississippi River, and 25 or 30 miles from the nearest land. The head of the sea valley is about 180 feet subsea.[6] Shepard (1937, p. 1352) gives 1 per cent as the approximate average gradient of the trough. The head

[6] The term subsea means below sea level. It comes out of the oil fields, where it may have been invented by a man who knew only the American language. Its parts, so happily joined, let no man lightly put asunder.

of the trough or valley is steeper, perhaps 1.6 per cent or about 85 feet per mile.

W. J. Osterhoudt (1946) reported the seismograph discovery of an ancient Mississippi River channel 35 to 70 miles west of the present river, extending from the vicinity of Houma, Louisiana, to the Gulf coast. J. Ben Carsey (1950, p. 373) showed a submarine extension of this channel, almost to the head of the sea valley. Osterhoudt described the filled channel as 'probably over 600 feet deep and perhaps more, 'han 5 miles wide". Presumably its gradient its almost as flat as the delta surface, that is only a fraction of a foot per mile. The profile of the sea valley, if extended landward from the valley head, would reach sea level in 2 or 3 miles. The same contrast in gradients exists here as between the Salinas Valley and other California filled channels on the one hand, and the Monterey and some other California sea valleys on the other. It is far from certain that the Mississippi filled valley connects with the unfilled sea valley. It is perhaps equally probable that the filled valley continues straight south from its last known position at the 10-fathom line, and reaches the steep continental slope 30 or 40 miles southwest of the sea valley.

The filled valley below Houma, and the sharply defined sea valley off shore, make a pair that I cannot explain. A subaerial orgin for the sea valley's uppermost part is probably ruled out by Steno's principle, as in the case of the Monterey valley head. Also, the sea valley's gradient is much too steep, even for a rejuvenated Mississippi. Some submarine process seems indicated, perhaps the scour by silt-laden gravity currents to be suggested on a later page. If so, why are not one or more similar steep-gradient sea valleys connected with the active Mississippi delta? Perhaps the slope of the delta is not steep enough. Shepard (1937) has called attention to the flat floor of the actual sea valley and suggested the possibility that it developed from a sink or trough initiated by the solution of one or more salt plugs. This hypothesis was discarded by Shepard. Perhaps it should be revived.

Congo Sea Valley

A steep-walled submarine gorge extends out into the Atlantic from the Congo estuary at least 130 miles from the African shore. At this point the gorge's bottom is 9444 feet below the surface of the sea (Veatch and Smith, 1939, p. 27), making the average gradient about 73 feet per mile, almost 1.5 per cent. For the first 40 miles from shore, the gorge is bounded by gently sloping continental shelf that is mostly less than 300 feet subsea. Farther off shore, the sea floor slopes much more steeply westward reaching 4200 feet subsea about 85 miles from shore. The canyon floor, in its first 65 miles (measured from Malela, Belgian Congo), drops 4400 feet, with a maximum relief in this stretch of about 4200 feet between canyon bottom and general sea floor. In the next 45 miles, the long profile of the canyon shows a series of steps, with a total drop of 2300 feet so that at 85 miles from the African coast the canyon bottom is 6900 feet subsea, and the local relief 2700 feet.

The Congo has partly filled its estuary with sediments. At the estuary's mouth the fresh water of the river makes a current only a few feet deep, floating on salt water from the ocean (Veatch and Smith, 1939, p. 29). A strong longshore current moves sand north along the Angola coast (Veatch and Smith, 1939, p. 28), and probably dumps its load into the gorge. What happens to this sand is something of a mystery.

Nazaré Sea Valley

Not all major sea valleys are off the mouths of rivers. Lautensach (1928, p. 302) noted that the 1000-meter deep Nazaré submarine canyon, 100 km. north of Lisbon, heads close inshore 3 km. north of the nearest stream mouth, and it a mere brook. On the other hand, the excellent Portuguese charts, unlike some older British charts, showed no sea valleys anywhere near the mouths of the large rivers Minho and Douro, not far to the north.

Shepard and Beard (1938) called Nazaré Canyon the probable ancient course of the Tagus, on which Lisbon is situated. No supporting geomorphic evidence was presented.

Valley Drowning by Downwarping

One possible origin for a sea valley is the downwarping of the distal end of a land valley. The long profiles of the lower courses of most great rivers, such as the Mississippi, and of many smaller rivers, such as the Salinas, are nearly horizontal. Imagine the effects if such a river were drowned as an incidental result of the general downwarping of a continental border. For one thing, the effects would be equally great along the whole coast. If old, pre-warping erosion surfaces could be recognized both on land and beneath the sea, their relief should be similar. If the warping were cylindrical, with the axis parallel to the general coast line, the long profile of the drowned valley would be convex upward. If the rate of downwarping were constant, shore erosion of interstream areas might be uniform, and its only apparent effect would be the flattening of the interstream ridges and the reduction of the relief between the submerged valley and its bounding ridges. If the downwarping were intermittent, terraces might be cut on the ridges but the relief between valley and ridges would be at least locally reduced. Finally, if the warping extended inland, its effects on the younger outcropping coastal sediments might be recognized.

Jessen (1936) attempted to explain the Congo sea valley as one of the effects of postulated periodic downwarping that carried the west margin of a series of Mesozoic and Cenozoic peneplains below sea level (Fig. 23). The sea valley was thought to have been cut in the early Tertiary, after the formation of peneplain 4. The submarine valley is up to 4200 feet deep, but the exposed part of peneplain 4 is today only 1300 feet above sea level. The warped Congo profile suggested by Jessen is a double curve, mostly concave, that of the peneplains and the actual sea floor simply convex (Fig. 23). Jessen assumed a simplicity of post-Cretaceous deformation not consistent with his own photographs or with Veatch's (1935, p. 30) statement: "The 2500 to 3000 meters of sediments deposited between the Aptian and the mid-Miocene were then intensely folded, faulted and eroded."

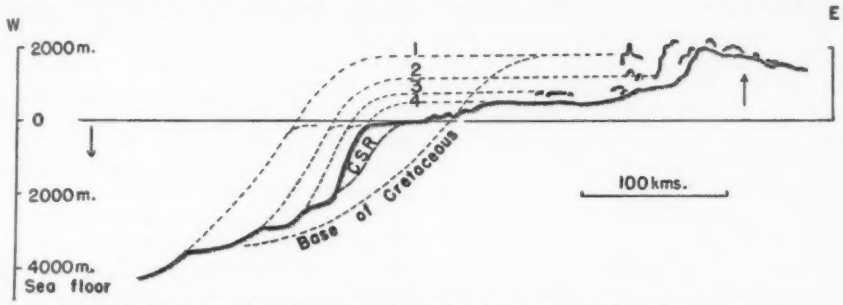

Figure 23.—Postulated Downwarping of Central African Peneplains (1–4) and Lower Congo (CSR)
After Jessen (1936)

Two of Jessen's figures were combined to make Figure 23, thereby superposing the long profile of the Congo on an east-west section 450–500 miles farther south. This superposition is not unfair to Jessen, but it does not conform to Veatch's idea (1935, p. 4) of the progressive post-Miocene sinking of the central part of the Congo Basin. The resulting deformation of the supposed peneplains is different from that postulated by Jessen. Veatch considered that the old rocks around Stanley Pool mark a zone of post-Miocene uplift, separating the main Congo Basin from the coastal basin of depressed and deformed Cretaceous and younger sediments. Veatch and Smith (1939, p. 23–31) develop the hypothesis that the Congo submarine canyon was cut in the weak post-Jurassic sediments by subaerial erosion beginning "not earlier than the Mousterian" late Pleistocene stage of human culture (Veatch and Smith, 1939, p. 26). The downwarping of the post-Jurassic sediments is

considered older; no post-canyon warping is postulated. The steep gradient of the Congo sea valley apparently did not disturb Veatch and Smith.

Emery (1950) suggested that downwarping of the continental slopes has submerged both the slopes and the canyons that locally incise them. His paper lacks diagrams, but his words suggest the hinging of the continental slopes at one margin and their rise and fall in a slow flapping movement. The flap off California, if real, is sinuous in plan, varies considerably in width, and lacks the postulated stream-cut valleys for long distances. Emery brings in Cascadia, Appalachia, and Catalinia. The evidence for Cascadia has not been convincingly presented in any publication with which I am familiar. King (1950, p. 653) doubts Appalachia as a persistent borderland. Catalinia was a small southern California land mass that apparently disappeared before canyon-cutting time. No surviving California sea valleys were cut into the margins of Catalinia. On the contrary, sea valleys indent the walls of basins that now occupy part of Catalinia's site. In spite of these general doubts, I feel that the continental shelf may be downwarped off the mouth of the Congo, beginning 40–45 miles from shore. This is, however, the region where Jessen recognized relatively flat terraces on the sea floor. The best evidence on the shapes of crystalline and sedimentary masses along continental margins will probably be seismic, and some such evidence is mentioned by Emery. Even if the continental slopes were downwarped, the inner parts of such trans-shelf sea valleys as the Monterey and Congo would remain to be explained. The Congo estuary may indeed be an elevated valley of submarine origin.

Submarine Modes of Valley Origin

It is easier to show that the Monterey and most other large, steep-headed sea valleys were not formed subaerially than to work out an acceptable hypothesis for their submarine origin. One line of study, however, seems especially promising.

Gravity currents of muddy water along the continental margins, similar to those known in lakes, need not be limited to the glacial melt waters postulated by Daly (1936). Two possibilities are suggested by analogy with occurences in the Swiss lakes (*see* Hydraulic factors in extensive water bodies). First, the upper part of Montery Canyon may possibly have had an origin similar to the trench in the floor of Lake Geneva off the mouth of the upper Rhone (Heim, 1919, p. 430), if the very silty Salinas River water is heavier than sea water. Monterey Bay and Salinas Valley mark a broad tectonic depression. For a long time, perhaps since the beginning of the Pleistocene, mud may have been deposited along at least one side of the Bay portion of the depression, while a channel was kept clear and graded to fit the hydraulic conditions. Second, repeated subaqueous slides or flows of the Zug type may have cut the submarine canyon and kept it clean. The Zug gradients—12 per cent at the source, 4.4 per cent mean—are similar to those of the Monterey and many other sea valleys (Monterey gradients 11.5 per cent for the first half mile, and varying widely about the mean of 3.86 per cent in the next 45 miles). The actual Monterey channel may have been localized by a combination of circumstances, including not only a gravity current from Salinas River and the slumping of Salinas River sediments, but perhaps also a secondary seaward current related to wind and wave induced long-shore currents.

Explanation by turbidity currents is not without its problems. One is presented by Carmel Canyon, a Monterey tributary that appears to be cut largely in granitic rock, possibly along a fault zone (Shepard and Emery, 1941, p. 89). Part of the course of lower Monr terey Canyon may be through granite rather than around it, but this has not been demonstrated.

Range of Eustatic Changes of Sea Level During Pleistocene

If we recognize sea valleys with steep gradients as products of marine processes, we may use estuaries and filled valleys with flat gradients to determine the positions of relatively recent—commonly late Pleistocene—low stands of the sea. Submerged valley floors in coastal California are graded to possible sea levels at 100 to 400 feet subsea. The exceptionally low

base of the Mississippi channel at 600 feet subsea (Osterhoudt, 1946) may have been depressed somewhat by the subsidence of the Mississippi Delta (Fisk, 1944). For this and other reasons, this channel may indicate a base level only 200 or 300 feet subsea. In the Old World, submerged channels have known or suspected floors at similar depths. Sandford (1934, p. 100) reported Nile alluvium in wells to depths suggesting grading to a level at least 275 feet below present sea level, though the date of the trench might be as ancient as Plio-Pleistocene. The "peneplain" of the Sunda shelf in the East Indies is submerged about 100 meters (Van Bemmelen, 1949, vol. IA, p. 301), though regional deformation of adjacent areas makes a eustatic explanation somewhat suspect here. In general, a late Quaternary submergence of about 300 feet seems probable (Daly, 1934, p. 183, 185, etc.).

Eustatic strand lines above present sea level may also exist. The evidence is conflicting and falls outside the scope of the present paper. The older literature was discussed by Daly (1934, p. 151–181).

Upson (1949) has described possible eustatic terraces up to 100-feet elevation in Santa Barbara County, California. Similar terraces are prominent all along the California coast. Almost everywhere higher terraces are also present. In Santa Barbara County, terraces up to 100 feet above the present streams are traceable into the corresponding marine terraces, but in Los Angeles and Orange Counties the relationships between stream and marine terraces are obscure. The best known terraces in the Los Angeles region are those at various levels up to about 1400 feet elevation, just west of Los Angeles harbor. Here even the lowest terrace is deformed (Woodring *et al.*, 1946, p. 109–110). The 100-foot terrace at Newport Bay, 22 miles southeast of Los Angeles harbor, slopes gently inland for 4 miles, until it disappears beneath an alluvial cover at about 30 feet elevation. No marine terraces have been found at 100 feet or higher elevations farther inland. Possibly even the extensive coastal terraces at and near 100 feet elevation are the result of deformation of the land.

Just east of the California Coast Ranges, a portion of the Great Valley is at sea level and freely connected with the ocean. The Imperial Valley of southeastern California is at or below sea level, and separated from the Gulf of California only by the delta of the Colorado River. No marine terraces at 100 feet or other elevations are known in the Great Valley or in Imperial Valley. On the other hand the rocky west side of Imperial Valley is marked by a freshwater terrace at sea level, with extremely numerous associated freshwater shells.

Despite the prevalent lack of evidence in California for a late Quaternary eustatic position of sea level, higher than the present, such a high stand may have existed, perhaps at 100 feet elevation, and the evidence obscured by deformation.

In the Old World, terraces at uniform elevations can be correlated over broad areas. The attention of investigators has been especially concentrated on the Mediterranean region. All across North Africa, from the Atlantic to the Red Sea, Quaternary terraces, mostly marine, are widespread at elevations of 90–100 meters (Sicilian stage); 55–60 meters (Milazzian stage); 30–35 meters and 18–20 meters (Depéret, 1926, p. 1410; Sandford, 1934, p. 52); with higher (Pliocene?) terraces up to 250–265 meters. Depéret found some of the same terrace levels on the north side of the Mediterranean. Somewhat similar coastal surfaces of stream and marine erosion, up to elevations of 125 meters, have been recognized in Portugal (Lautensach, 1928, p. 303, 305, 307, etc.), but notably deformed, with a range of 100 meters in the elevation of a single terrace in the vicinity of Oporto.

Baulig (1935, p. 19) thought that he could extrapolate the long profiles of the upper courses of many French rivers to Depéret's set of high base levels (and others up to 400 meters). Other workers have disputed the extension of the Mediterranean levels to all parts of France (Depéret, 1926, discussion, p. 1426–1428; Denizot, 1949). Denizot considers the Milazzian a sub-stage of the Sicilian, and finds their equivalents, with the earliest *Elephas antiquus* fauna, along the lower Seine and Somme in northern France at 30 to 40 meters elevation. All authors who deal with the Atlantic coast of France are more or less puzzled by the lack of marine terraces there.

East of the Mediterranean, most of the Ara-

bian peninsula is probably a tilted block, elevated at the west, depressed along the Persian Gulf. The Gulf deepens gradually to a maximum of about 60 fathoms near its eastern shore. On the Arabian side, traces of sand dunes are submerged, and the only terrace is at 1-meter elevation (R. A. Bramkamp, personal communication). The gulf may be a fairly new feature, but the present gentle eastward slope of the Arabian block—much less than 1°—has existed long enough that the desert wadis have developed adjusted slopes for hundreds of miles inland. Nothing in eastern Arabia supports the idea of a eustatic erosion surface above present sea level. The possibility of concurrent lowering of both land and sea is not excluded by the evidence.

This brief review suggests that the relative drop in sea level recorded by the Mediterranean terraces may have been partially or entirely non-eustatic. In that case, almost all the Mediterranean lands rose together during the Pleistocene.

Geomorphic Significance of Pleistocene and Earlier Fluctuations of Sea Level

Some eustatic changes of sea level (perhaps between 100 feet elevation and 300 feet subsea) seem to be demonstrated for the Pleistocene, and their glacial control now seems highly probable (Daly, 1934). In addition, many widespread changes of level have occurred that may or may not be eustatic. Some of these may be Pliocene or older.

Erosion surfaces are of course the products of repeated graving by the same tools. Frequently the repetitions are separated by intervals that are geologically long. Exhumed, slightly modified old surfaces may be more common than is generally recognized. The Harrisburg peneplain of the southern Appalachians (Wright, 1934; 1936) seems to be a deceptively simple product of a long and complex history (King, 1949), a Tertiary surface having been much modified in the development of a later, probably Pleistocene, surface. Some Appalachian valleys were cut at least as long ago as the early Eocene (Cloud and Brown, 1944), at least partially filled with continental sediments, and then exhumed.

In central Europe, the complications of geomorphic history are especially well known. The Rhine and Danube have been discussed on previous pages. In the French Alps, discharges and gradients correlate fairly closely (Fig. 13). The long profiles published by de la Brosse (1905–) are surprisingly smooth, considering the rockiness of some gorges and the obvious effects of glaciation at the headwaters. Pre-glacial development of approximately, but not exactly, the present profiles is a likely explanation, perhaps the only one.

The San Gabriel Mountains of southern California (Fig. 19) are made up of crystalline rocks that contributed to the clastic Miocene and Pliocene sediments of the Los Angeles Basin. By the end of Pliocene time, mature stream profiles may have developed in the San Gabriel Mountains. Then the range was uplifted, with marginal faulting, and part of the adjacent Los Angeles Basin sediments were folded. Subsequently mature profiles have developed along the San Gabriel River and other streams which flow out of the crystalline ranges, across folds in the Miocene and Pliocene sediments and finally into the sea at grade. Thousands of feet of weak Los Angeles Basin sediments have been eroded in post-Pliocene time, but perhaps only a few hundreds of feet of crystalline rocks in the San Gabriel and other high ranges. The mountain valley of the San Gabriel River may have been excavated mostly in pre-Pleistocene time.

In general, an approximately smooth concave long profile may be of complex origin, the result of a long history of erosion, eustatic changes, tilting, integration of drainage lines, etc. Present profiles are not only inherited from the past, in some areas they may even represent the approximate restoration of earlier surface forms.

Conclusion

Even though the Davisian assumption of rapid initial uplift, followed by stillstand unto peneplanation, is so contrary to fact in some mobile belts that it leads to misunderstanding rather than to clear analysis, one element of the Davis system, grade as a measure of stream maturity, is useful in coastal California and no

doubt elsewhere. Some streams, even in the mobile belts, are mature and others have undergone fairly simple rejuvenation.

The slope of the graded long profile decreases almost continuously downstream. The curve, however, is not usually one that can be extrapolated precisely from a mathematical formulation or graphic extension of its upper or middle or lower portion, or even from its upper and middle portions taken together. The mature curve may actually steepen downstream, where bedrock is moderately resistant, or below the mouth of a steep tributary, or at the head of an alluvial cone. Sharp nickpoints may develop in several ways, but they persist only under special circumstances, and the most durable circumstance is the presence of a rock belt so resistant that it forms a local base level.

The correlation of stream terraces by their elevation above sea level is obviously dangerous, and in a mobile belt the use of their elevations above present streams may be little safer. Every case must be studied separately, and judged on its own merits.

Nevertheless, if adequate precautions are taken, the gradients of streams and of stream terraces become valuable geomorphic evidence. In this paper, their study has been used to indicate that steep-gradient submarine canyons in general, and Monterey Canyon in particular, should be excluded from the category of stream-cut topographic forms.

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MANUSCRIPT SUBMITTED TO THE SECRETARY OF THE SOCIETY, SEPTEMBER 7, 1950